Jet Propulsion Laboratory
California Institute of Technology

NASA Robotic Pioneers on Mars
and the Simulators that Drive them

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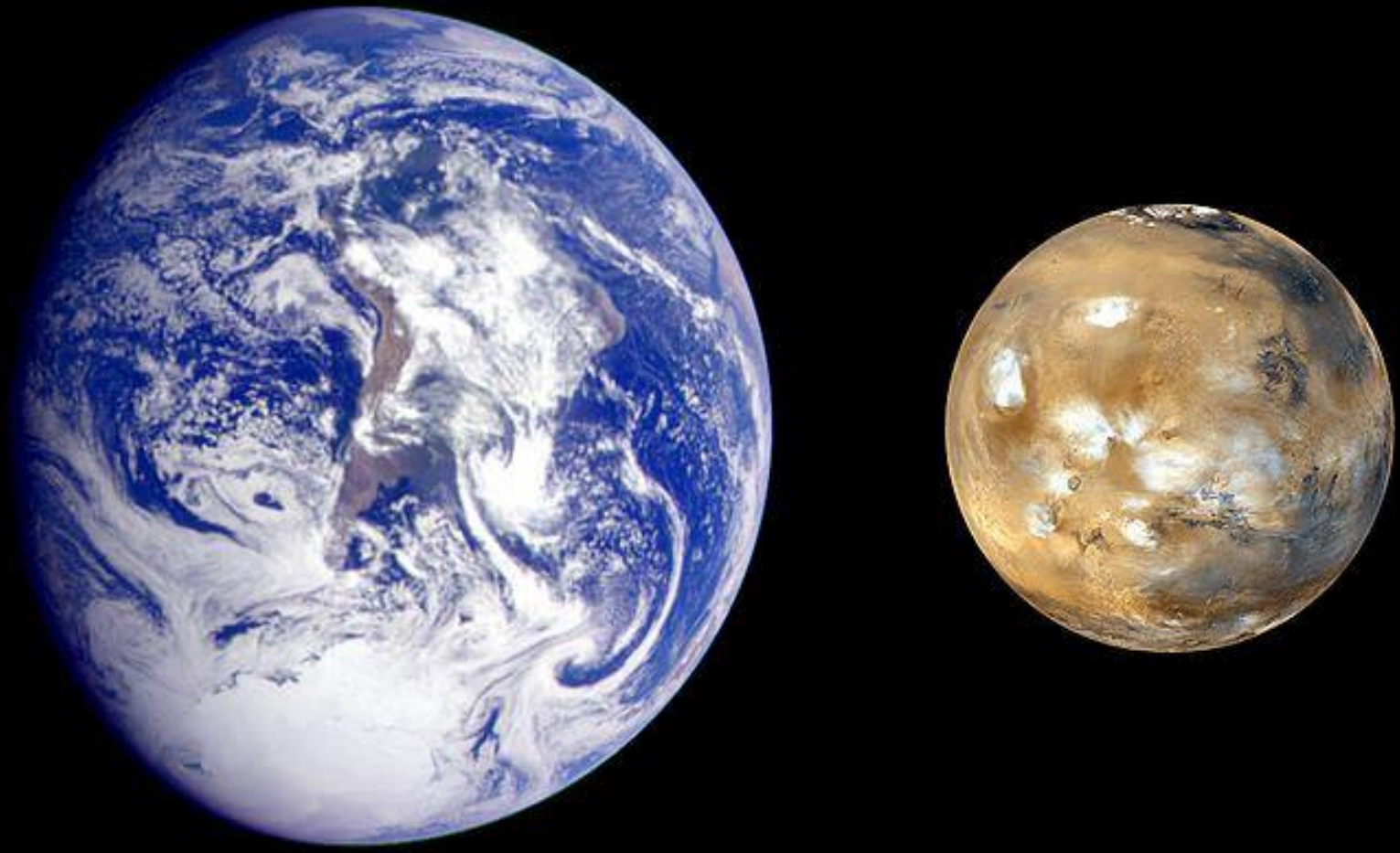
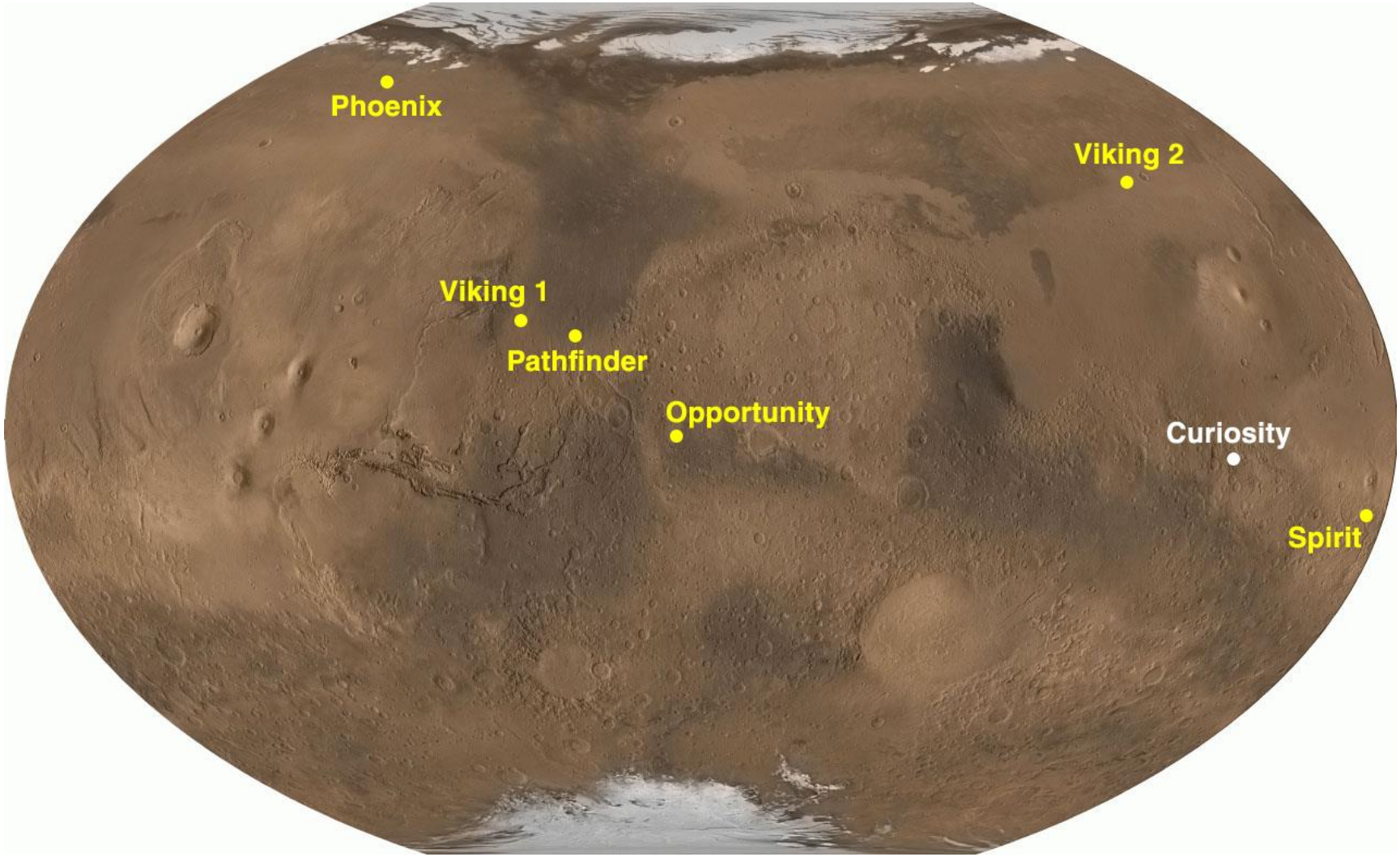
NASA Jet Propulsion Laboratory, California Institute of Technology
04/20/2018
Robotics SeminarUniversity of Maryland

MARS

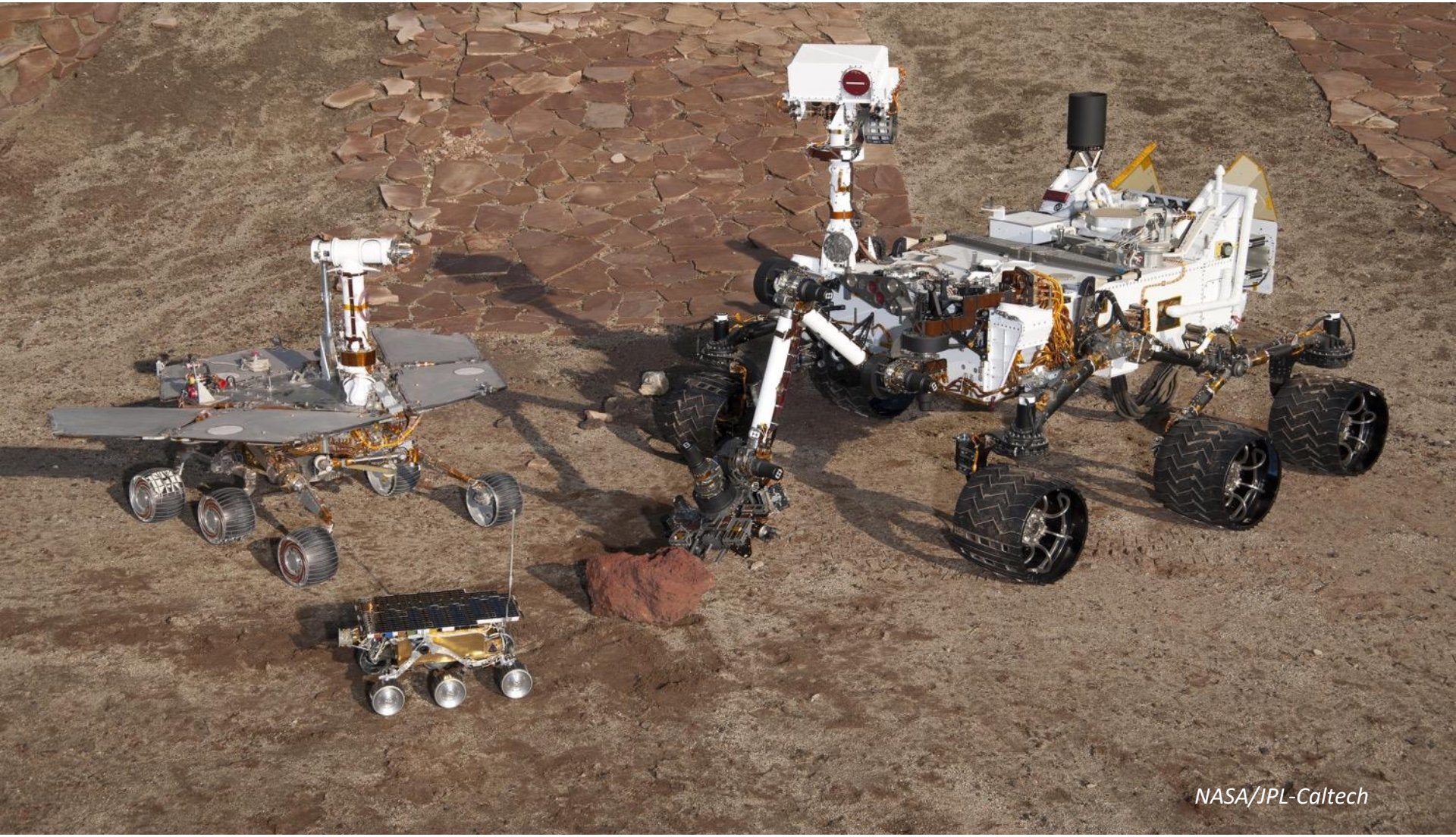


NASA/JPL-Caltech

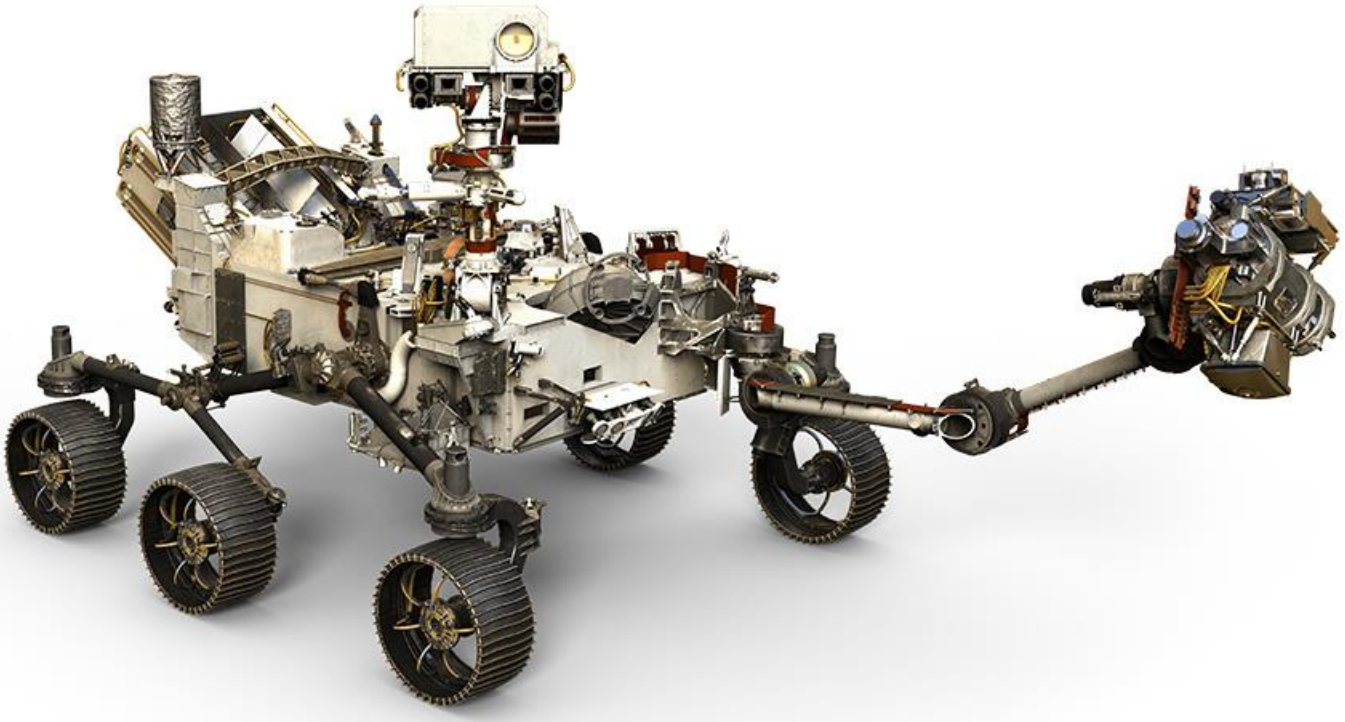
LANDING SITES



PAST AND CURRENT

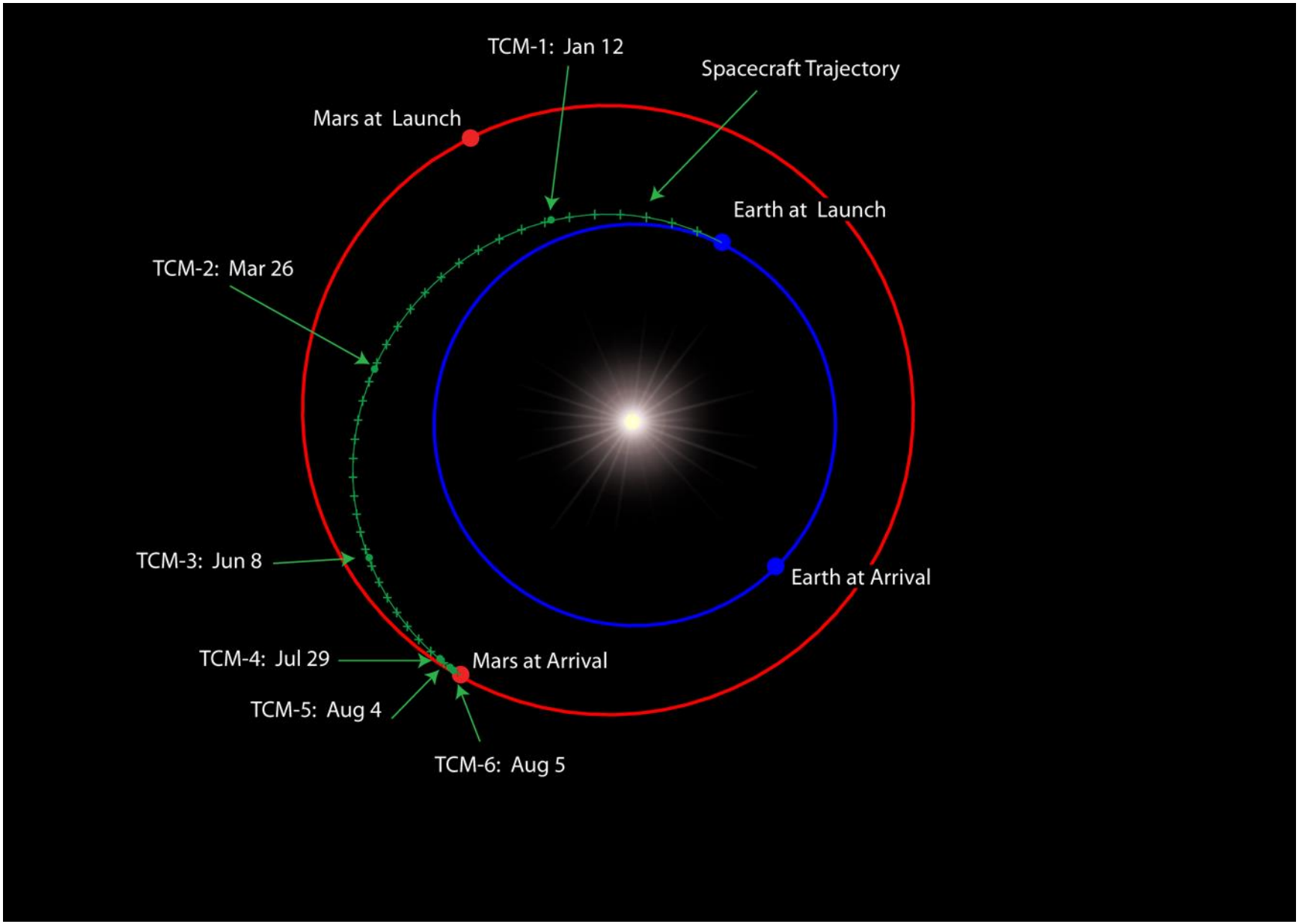


MARS 2020



NASA/JPL-Caltech

CRUISE TRAJECTORY



SPACECRAFT ASSEMBLY FACILITY

NASA/JPL-Caltech

LAUNCH

https://mars.nasa.gov/msl/multimedia/videos/?v=34

NASA/JPL-Caltech

ENTRY DESCENT AND LANDING

https://mars.nasa.gov/msl/multimedia/videos/?v=34

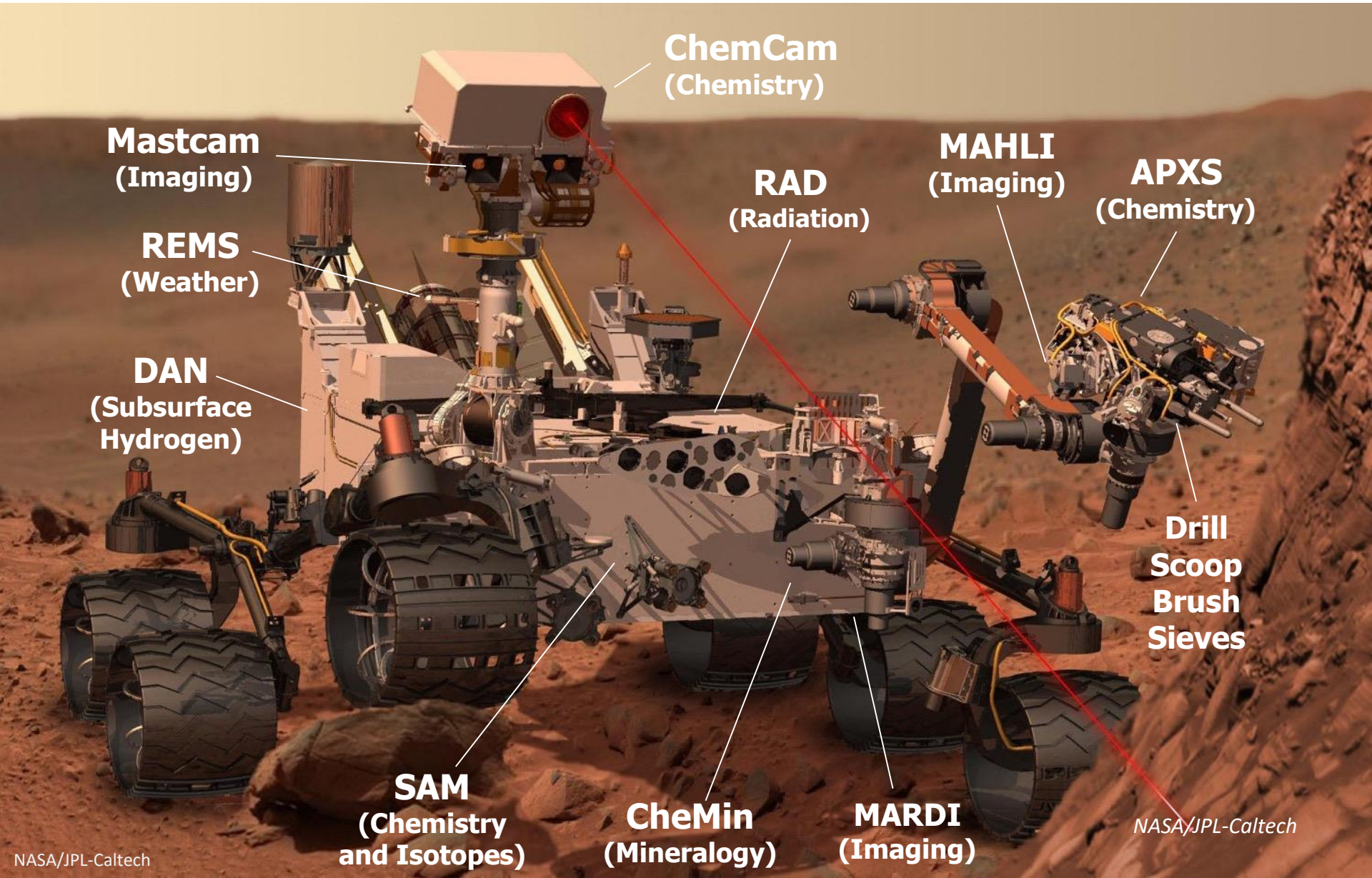
NASA/JPL-Caltech

FLIGHT SOFTWARE

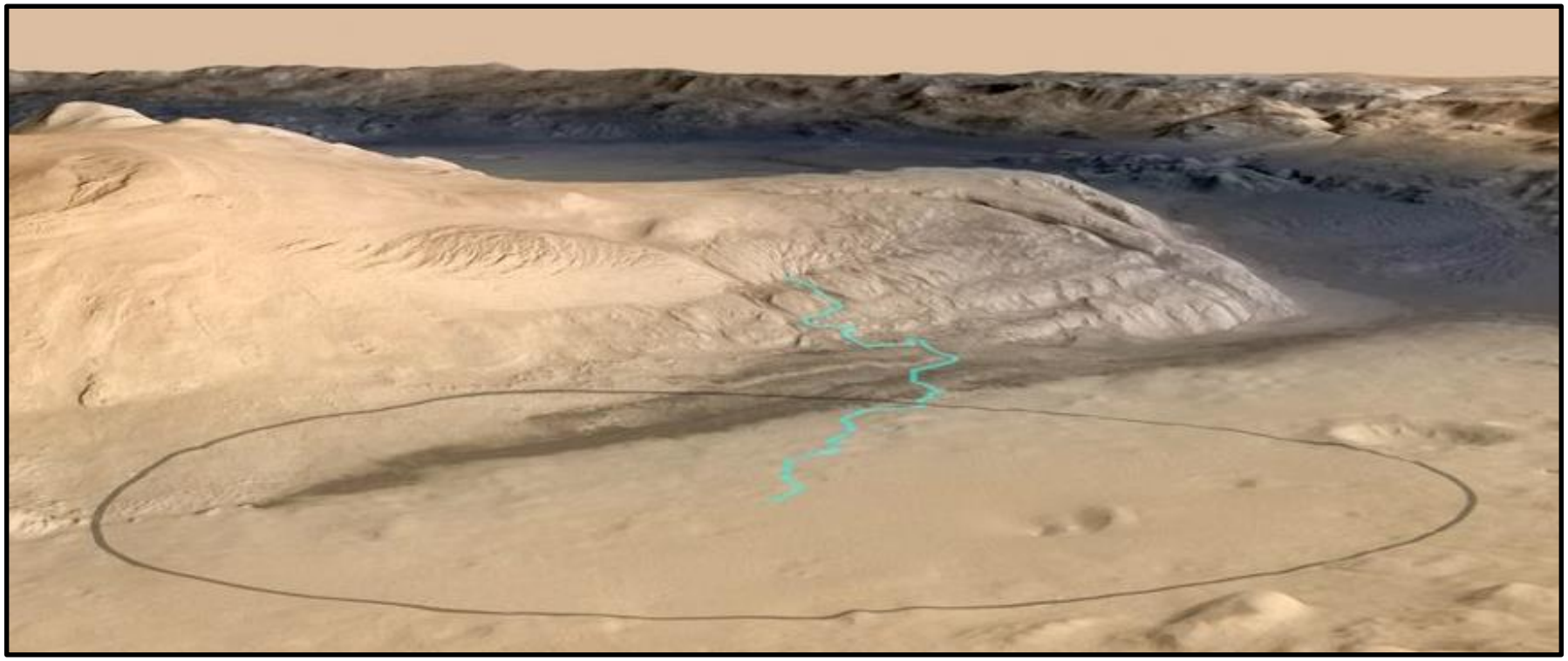
"I'm not worried that the radar will not perform. We've tested the hell out of that, and we got good performance off the radar. I'm not worried that the engines are not going to fire. I'm not worried that the parachute's not going to inflate, but I am worried that there's a bug in the software that we haven't caught yet, and that we don't know about, and it will come and bite us on a bad day."

— MSL Project Manager, Pete Theisinger, from the August 1, 2011 issue of Aviation Week

SCIENCE PAYLOAD



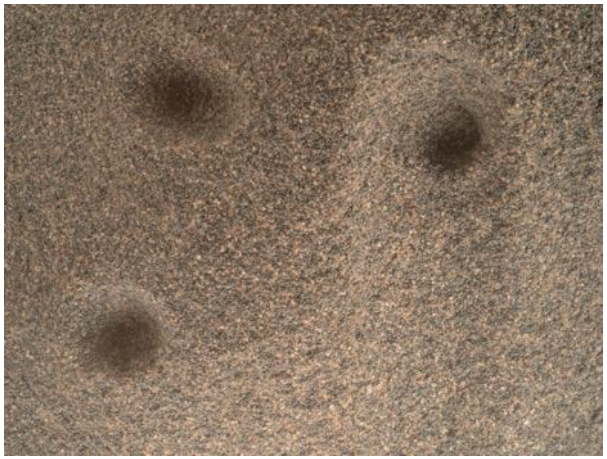
MOUNT SHARP



NASA/JPL-Caltech/Goddard

CONTACT SCIENCE

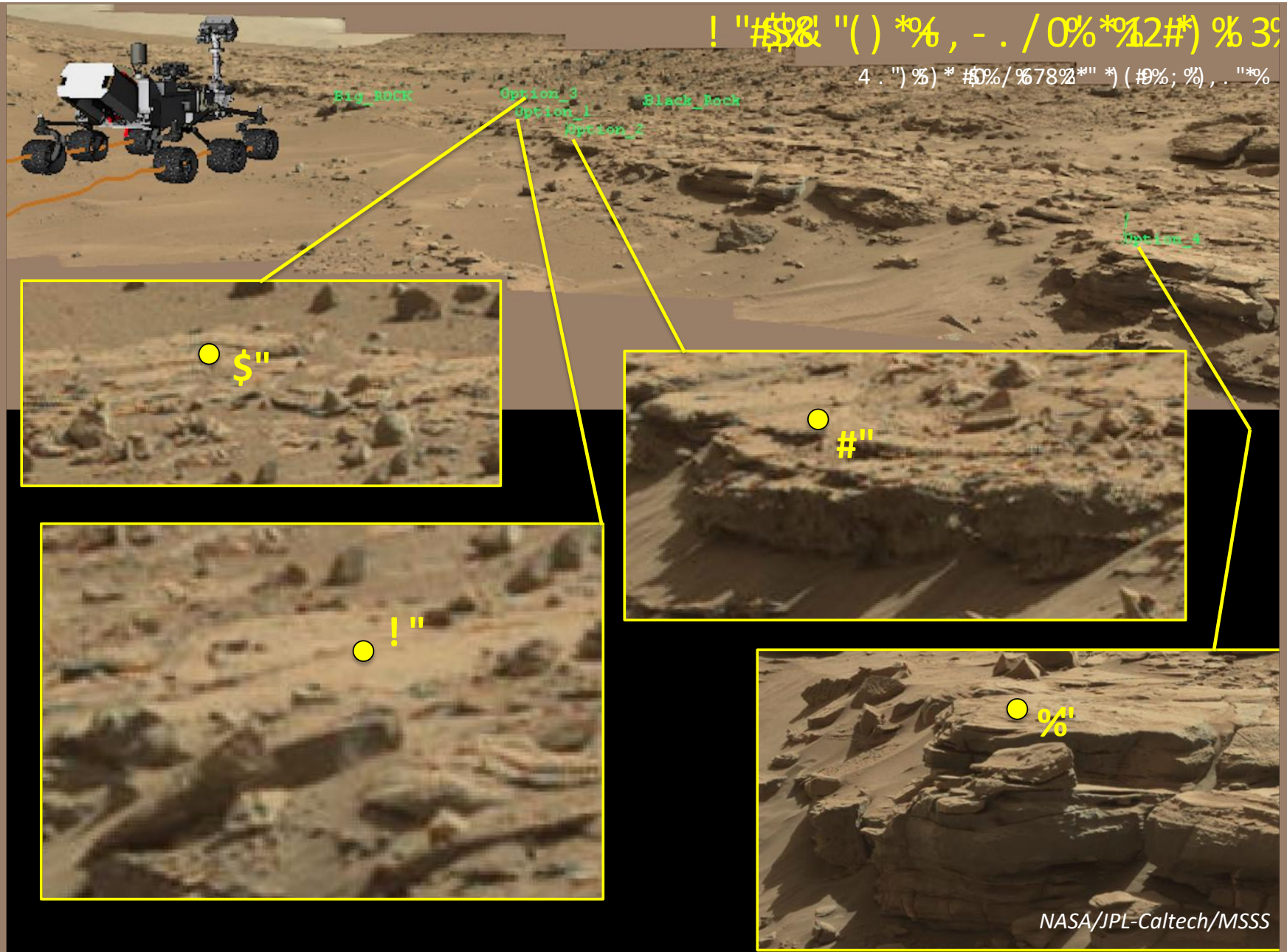
19 mm diameter



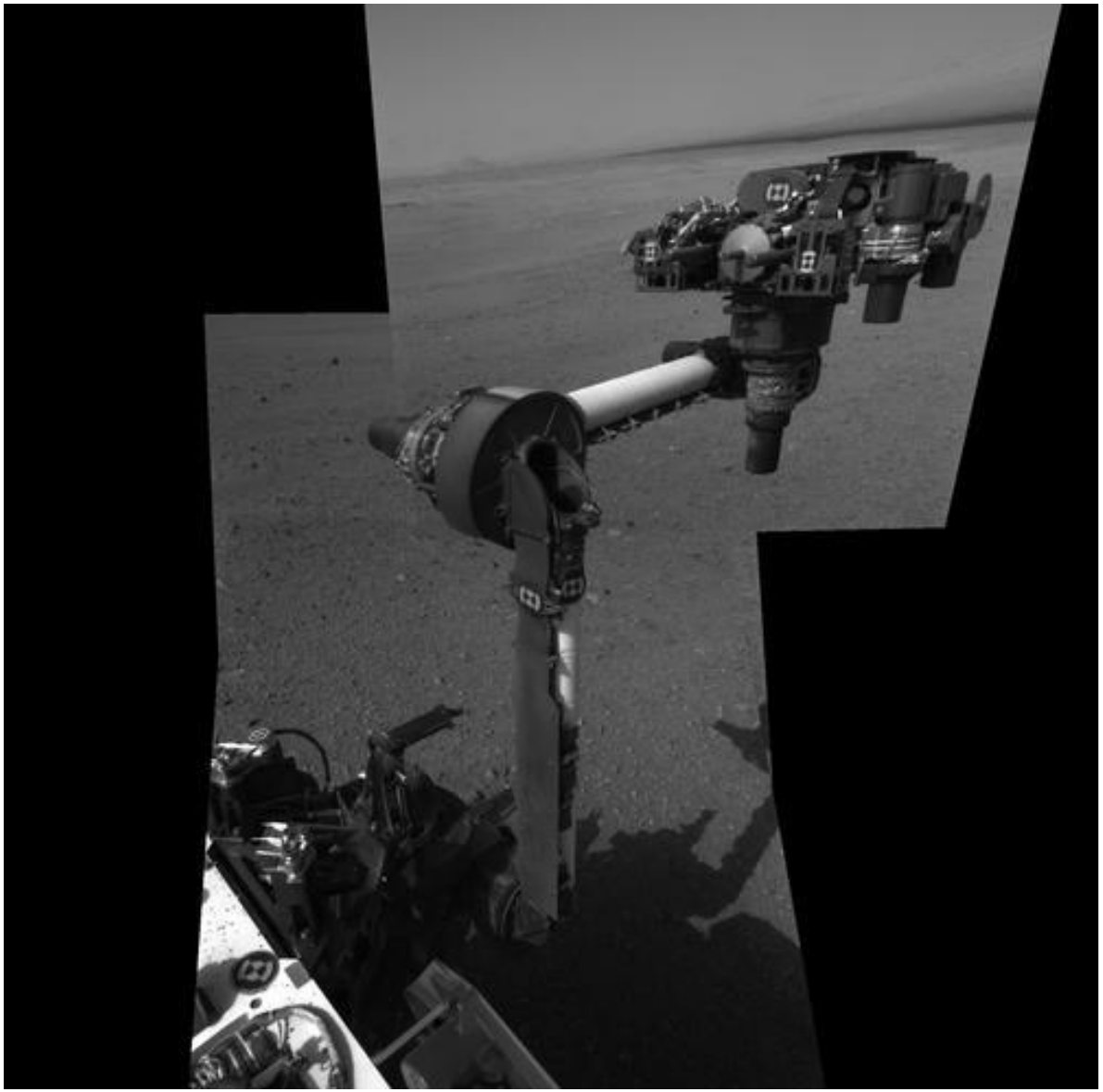
MAHLI at 5mm poker standoff

NASA/JPL-Caltech, MSSS

EVALUATING POSSIBLE DRILL TARGETS

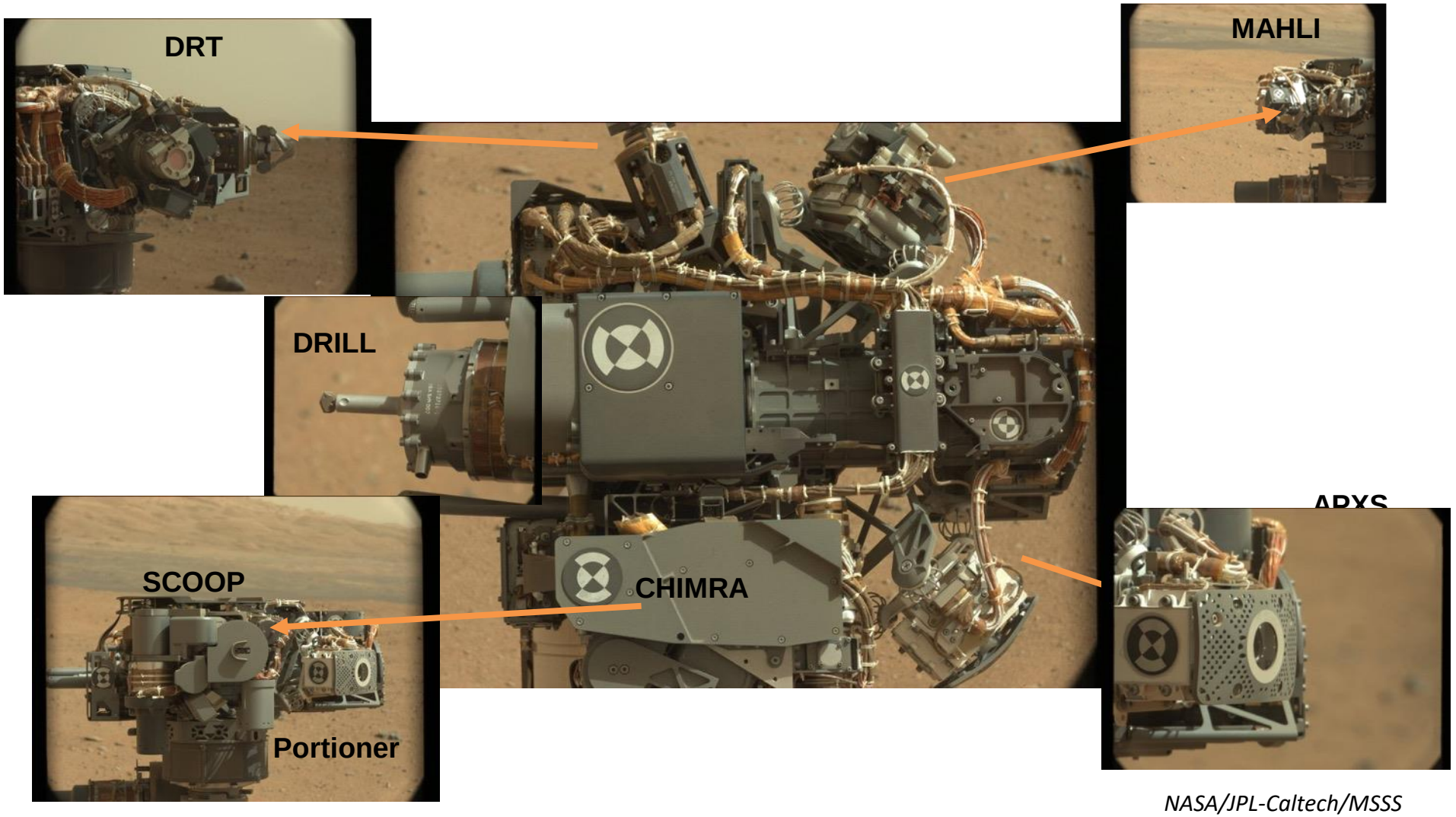


ROBOTIC ARM



NASA/JPL-Caltech

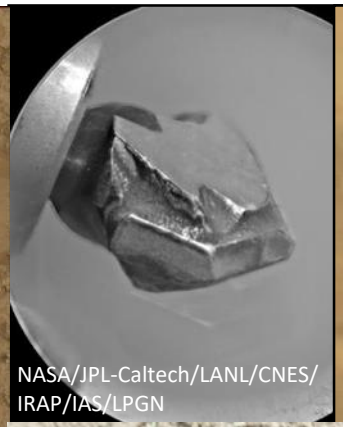
TURRET



NASA/JPL-Caltech/MSSS

DRILLING

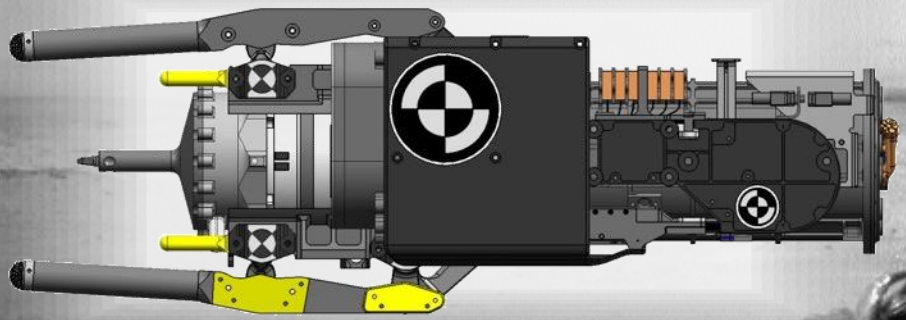

NASA/JPL-Caltech/MSSS


NASA/JPL-Caltech/LANL/CNES/
IRAP/IAS/LPGN


NASA/JPL-Caltech/MSSS

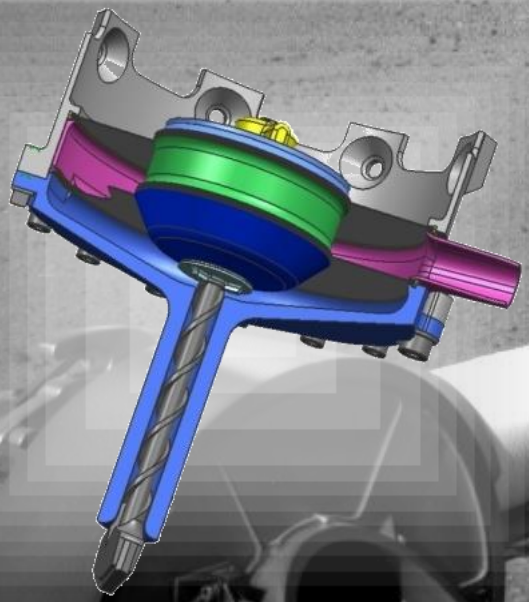

2 mm
NASA/JPL-Caltech/MSSS

Top View of Curiosity's Drill



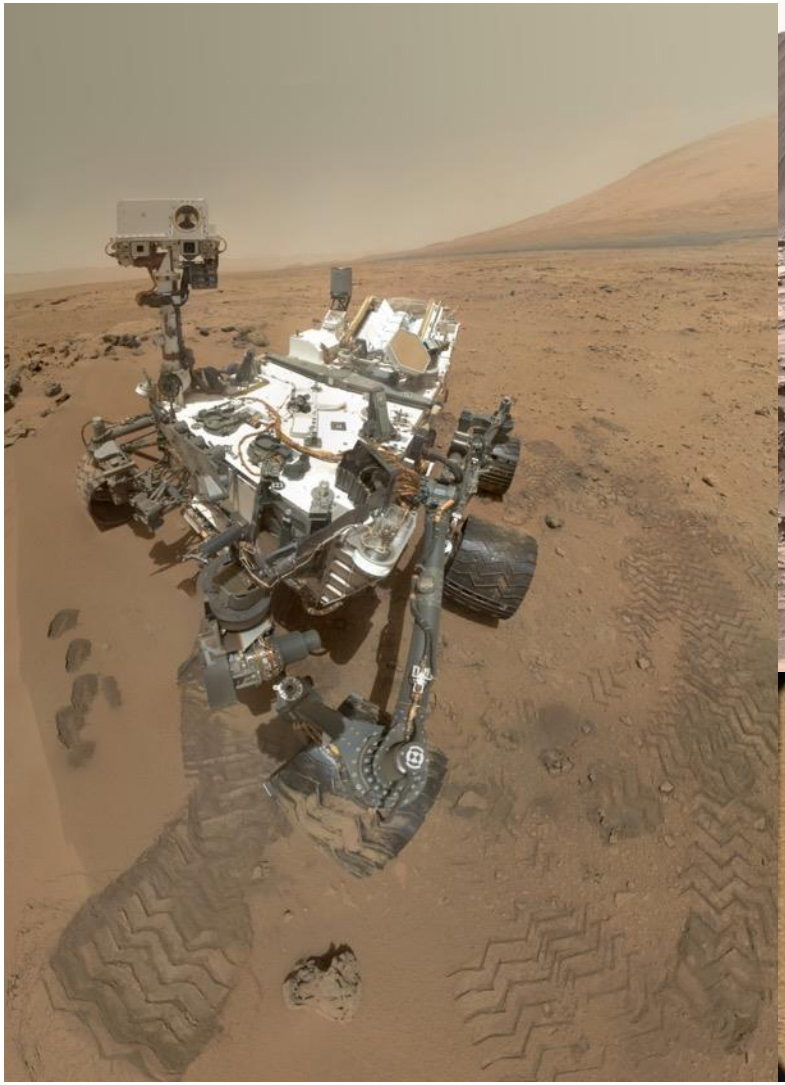
Curiosity's Turret

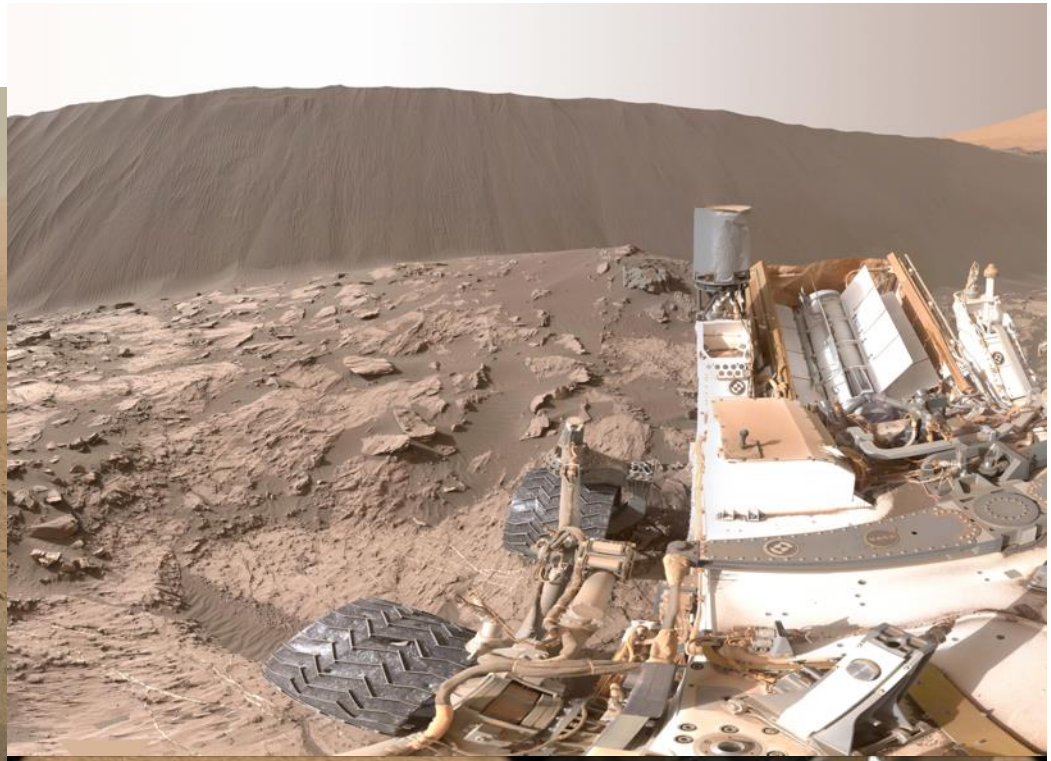
Section View of Curiosity's Drill Bit



Drill Specifications	
Spindle Rotation Rate	107 RPM
Spindle max torque	4.8 N-m
Percussion impact energy	0.05 to 0.8 J
Percussion rate	1800 BPM
Bit retraction force	4600 N
Translation stroke	65 mm beyond contact plane
Contact Sensing	Trigger force < 40 N
Bit Release capability	Full rover Mars weight on 20° slope
Structural capability	Full rover Mars weight on 20° slope

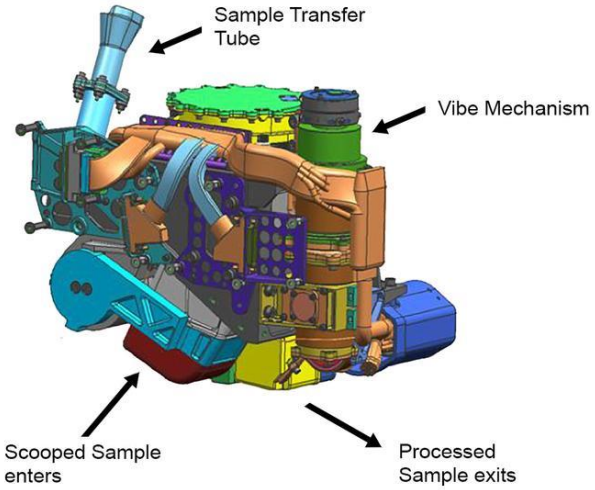
SCOOPING



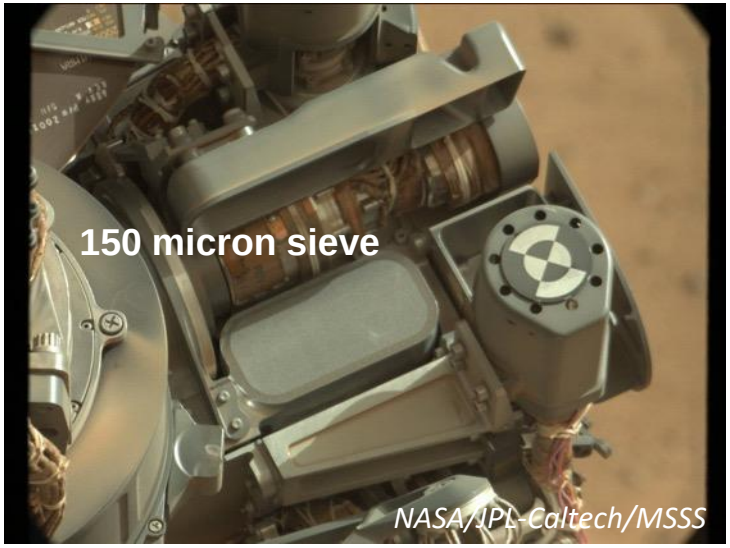


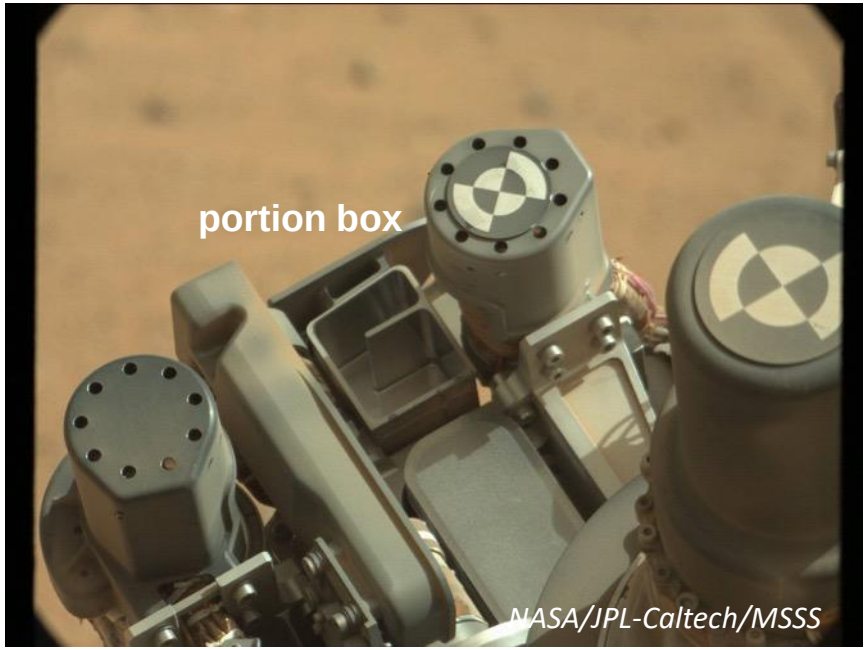
NASA/JPL-Caltech/MSSS

SAMPLE PROCESSING

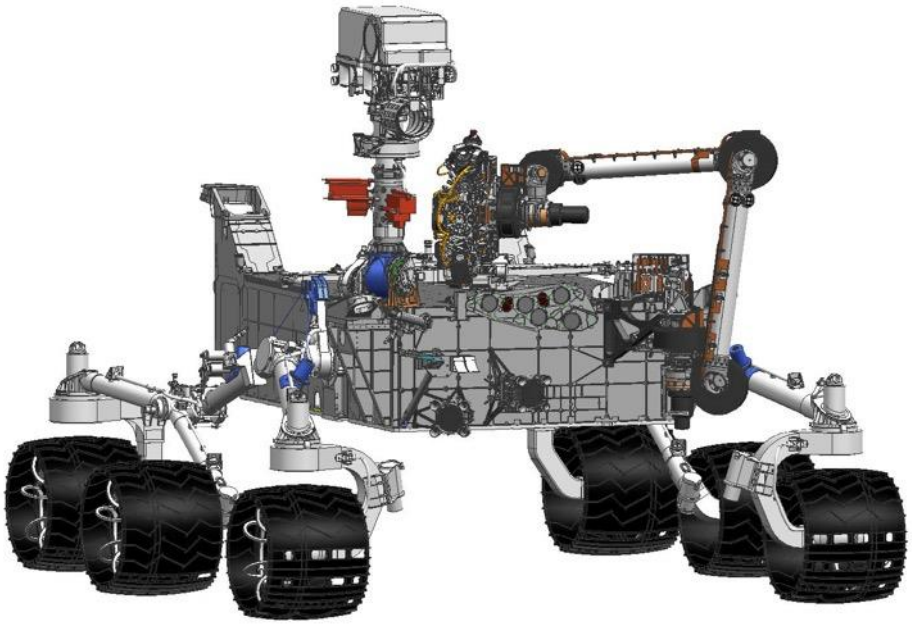


NASA/JPL-Caltech

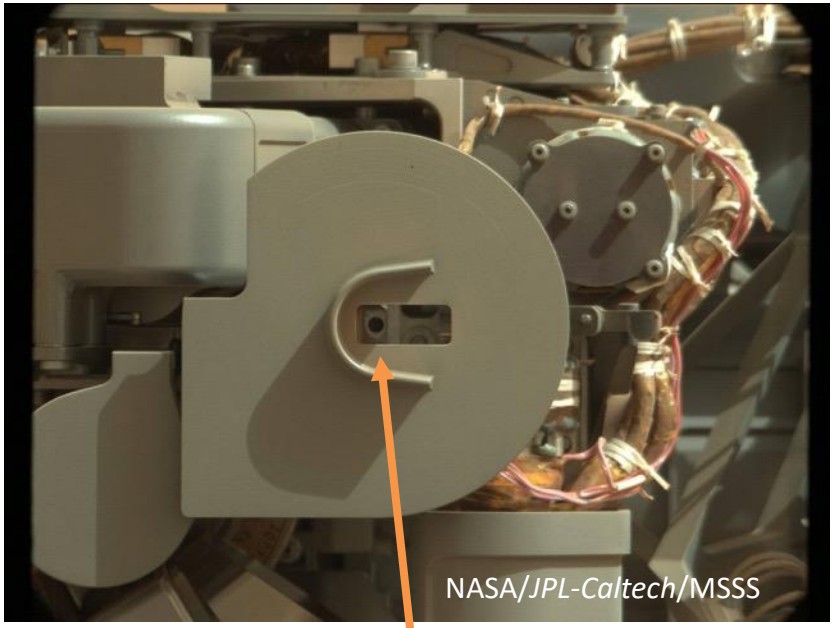




SAMPLE DELIVERY

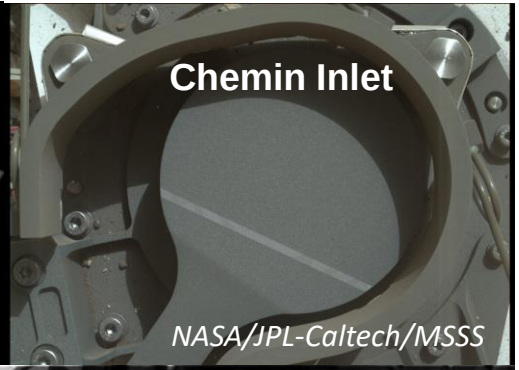


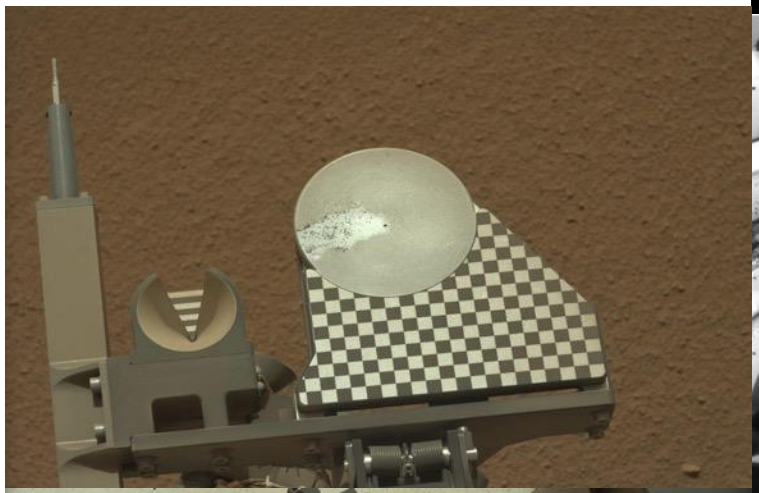
NASA/JPL-Caltech

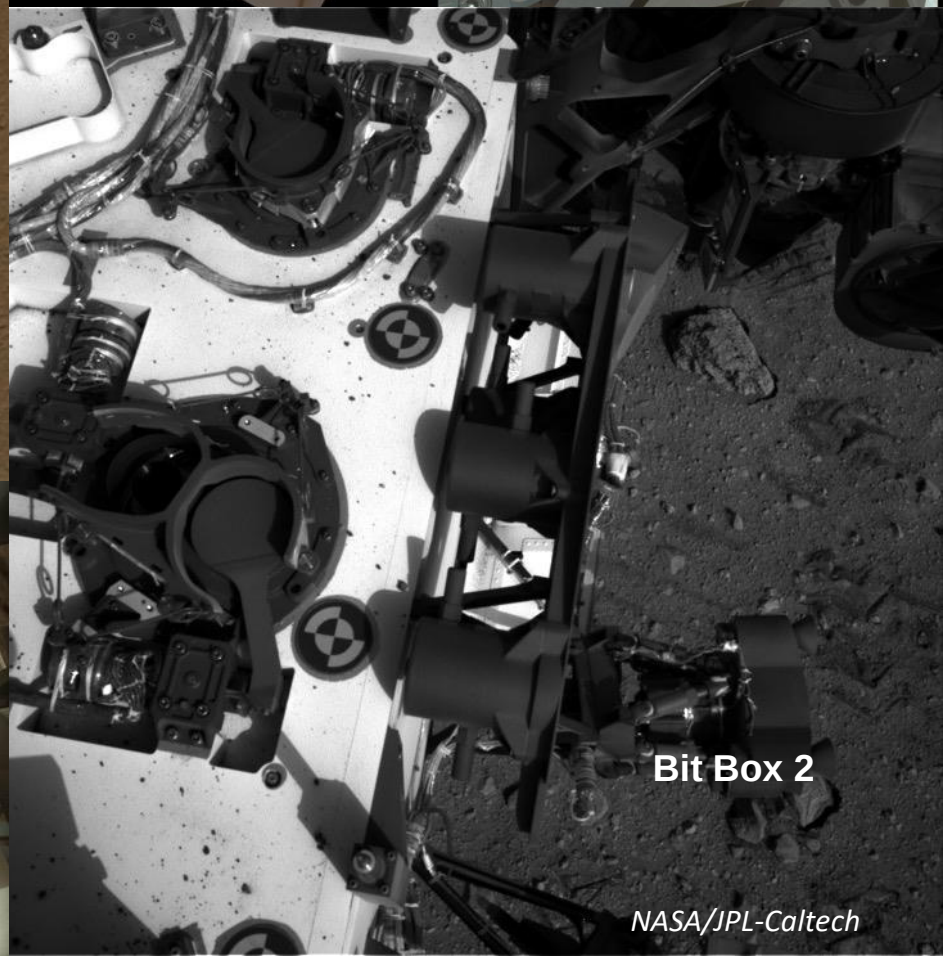


Portion Hole
3 mm diameter

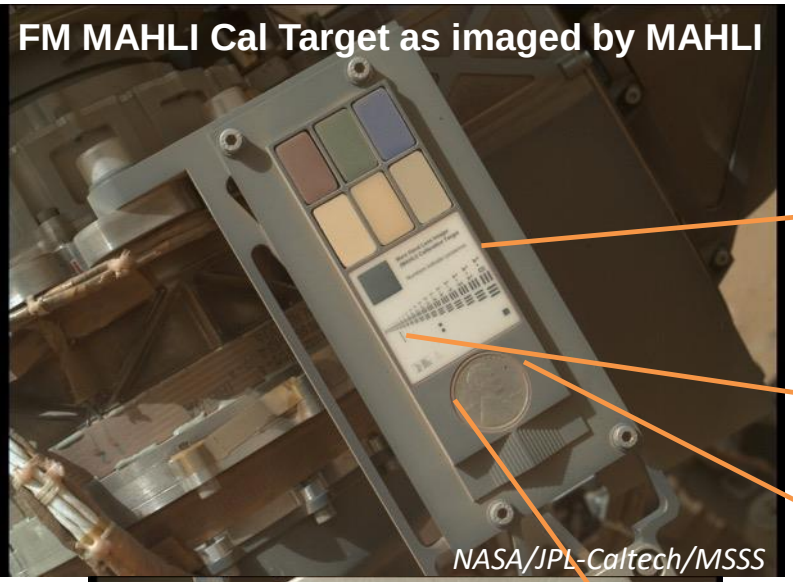
ROVER WORKSPACE

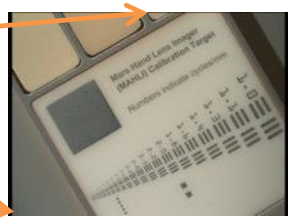


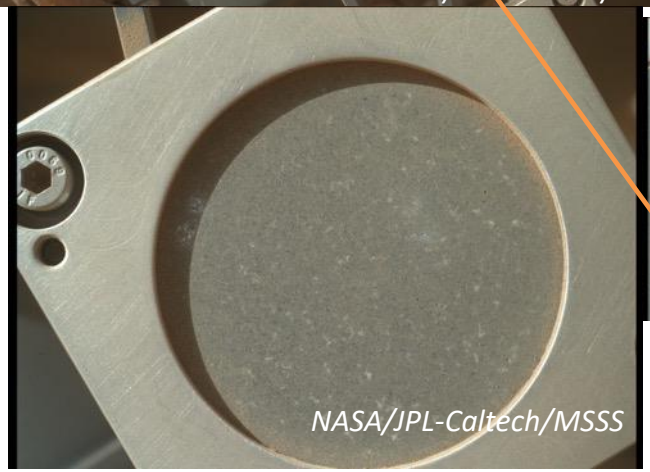


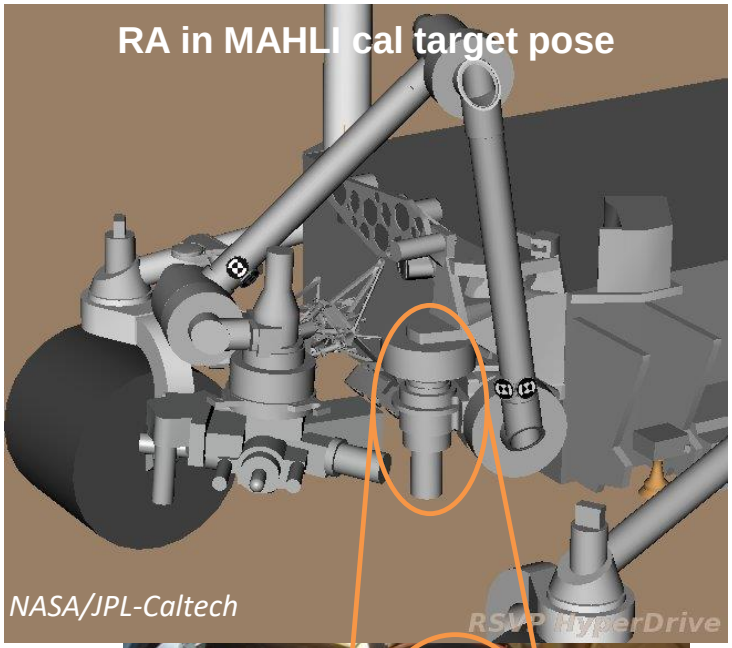


MAHLI and APXS Cal Targets

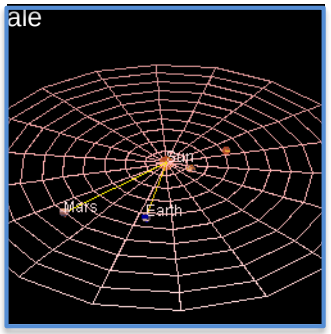








BECAUSE OF THE DISTANCE BETWEEN EARTH AND MARS, WE CAN'T DRIVE THE ROVER IN REAL TIME



MRO, Mars Odyssey, MEX

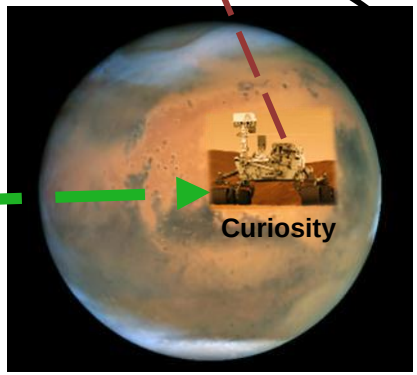
Deep Space Network
70m (230 foot) antenna

Spain

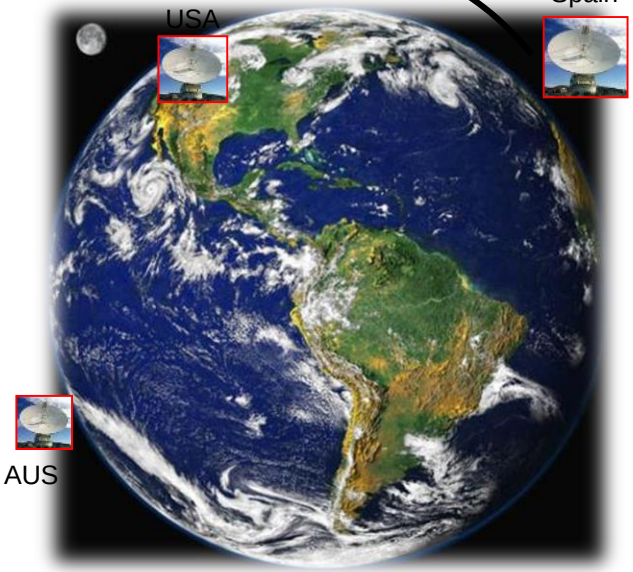
USA

Up to 24 minute delay

Up to 249,000,000 mi



Mars' Rotation: 24.65 hour Sol

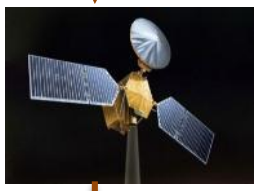


AUS

Earth's Rotation: 24 hour day

ROVER OPERATIONS

Rover Awake | Rover Asleep | Rover Awake



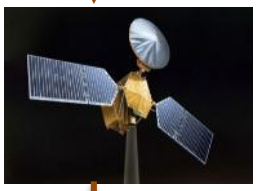
Data

Create the uplink 8:00pm

Commands for 1-3 Sols

ROVER OPERATIONS

Rover Awake | Rover Asleep | Rover Awake



Data

Downlink analysis

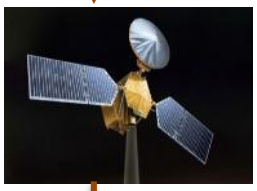
Commands for 1-3 Sols

ROVER OPERATIONS

Rover Awake

Rover Asleep

Rover Awake



Data

Planning

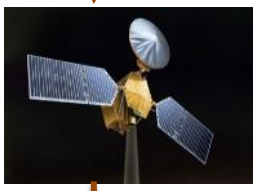
Commands for 1-3 Sols

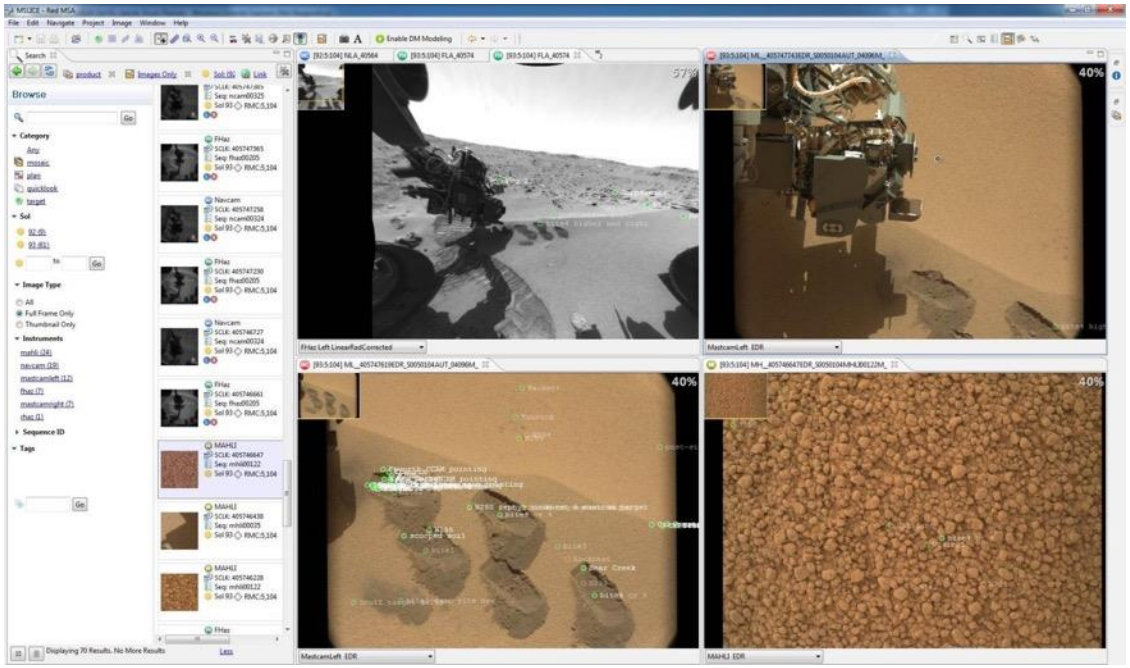
ROVER OPERATIONS

Rover Awake

Rover Asleep

Rover Awake





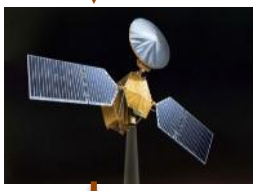
Data

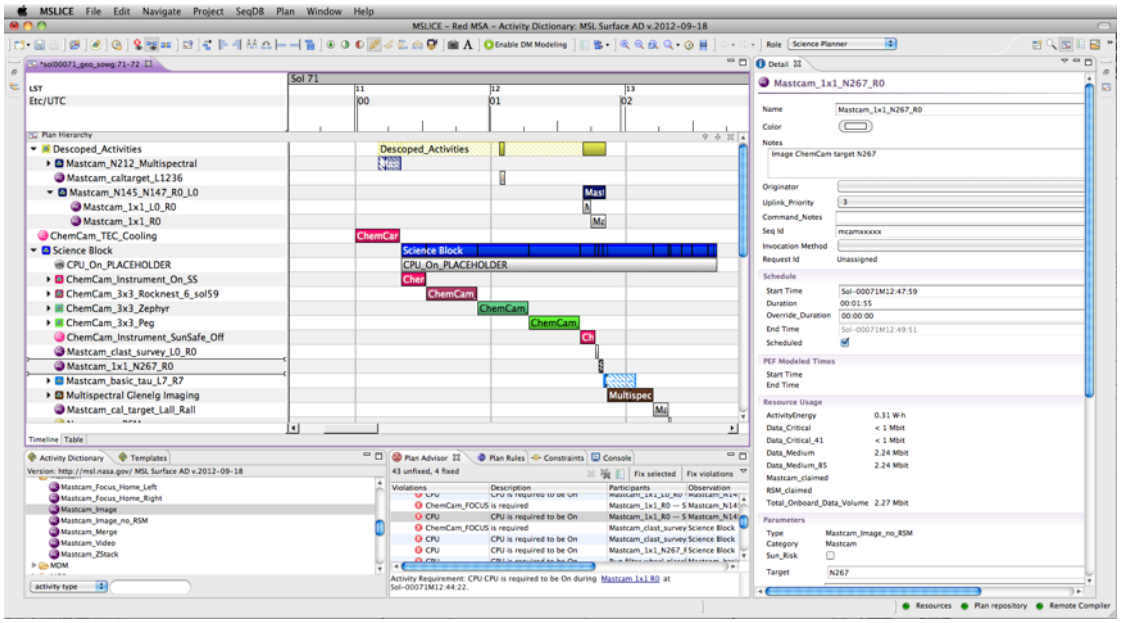
Planning

Commands for 1-3 Sols

ROVER OPERATIONS

Rover Awake | Rover Asleep | Rover Awake





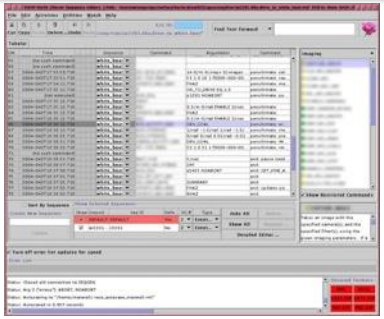
Data

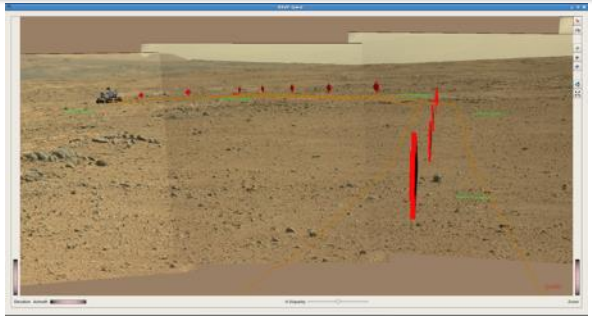
Planning

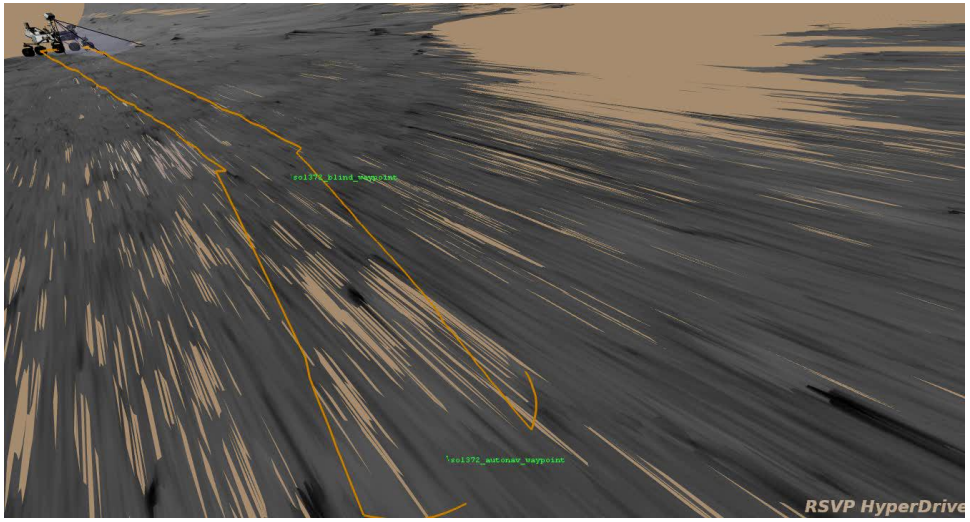
Commands for 1-3 Sols

ROVER OPERATIONS

Rover Awake | Rover Asleep | Rover Awake







Data

Sequencing

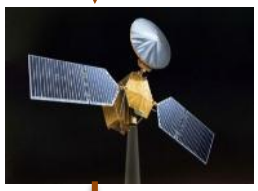
Commands for 1-3 Sols

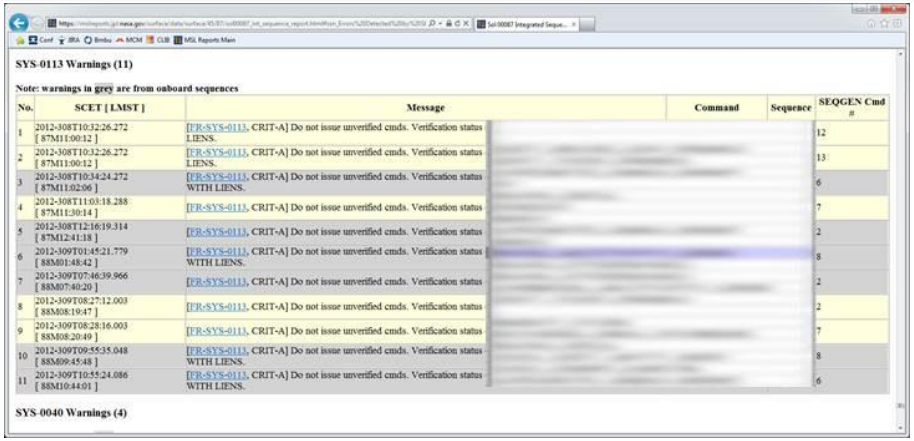
ROVER OPERATIONS

Rover Awake

Rover Asleep

Rover Awake





SYS-0113 Warnings (11)

Note: warnings in grey are from onboard sequences

No.	SCET [LMST]	Message	Command	Sequence	SEQGEN Cmd #
1	2012-308T10:32:26.272 [87M11:00:12]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status LIENS.			12
2	2012-308T10:32:26.272 [87M11:00:12]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status LIENS.			13
3	2012-308T10:34:24.272 [87M11:02:06]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			6
4	2012-308T11:03:18.288 [87M11:30:14]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			7
5	2012-308T12:16:19.314 [87M12:41:18]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			2
6	2012-309T01:45:21.779 [88M01:48:42]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			8
7	2012-309T07:46:39.966 [88M07:40:20]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			2
8	2012-309T08:27:12.003 [88M08:19:47]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			2
9	2012-309T08:28:16.003 [88M08:20:49]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status			7
10	2012-309T09:55:35.048 [88M09:45:48]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			8
11	2012-309T10:55:24.086 [88M10:44:01]	[FR-SYS-0113, CRIT-A] Do not issue unverified cmds. Verification status WITH LIENS.			6

SYS-0040 Warnings (4)

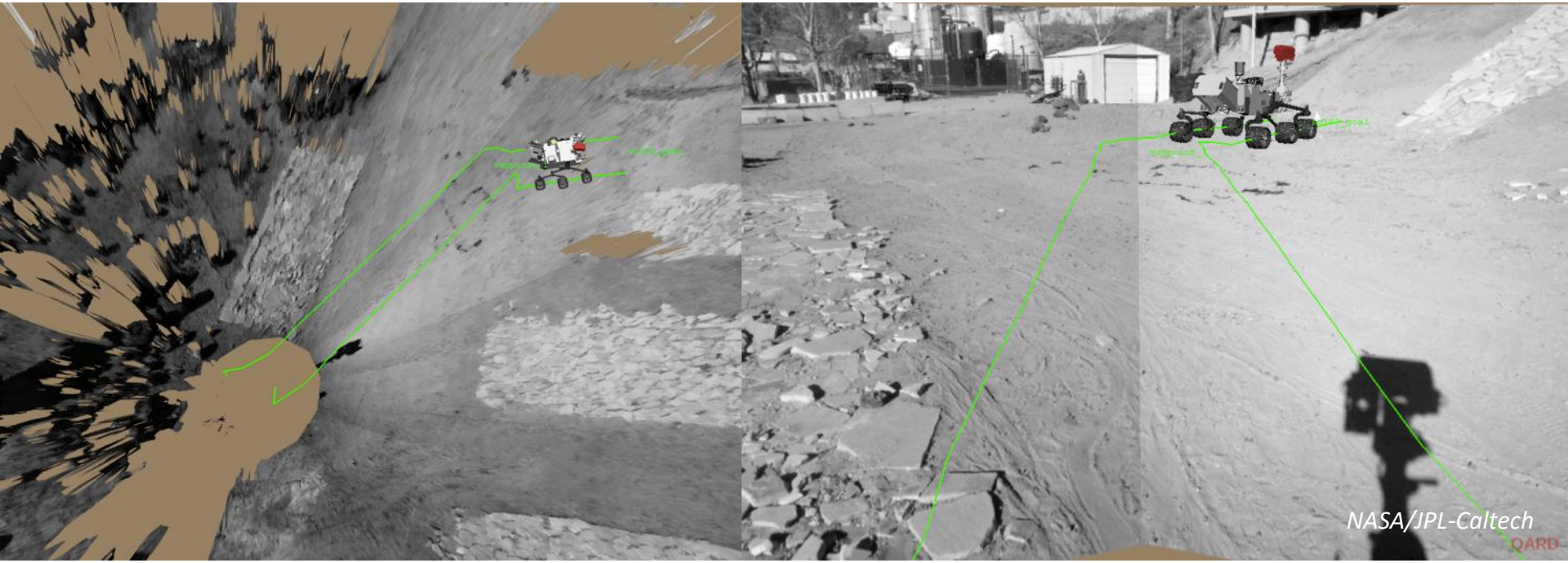
Data

Validation and Uplink

Commands for 1-3 Sols

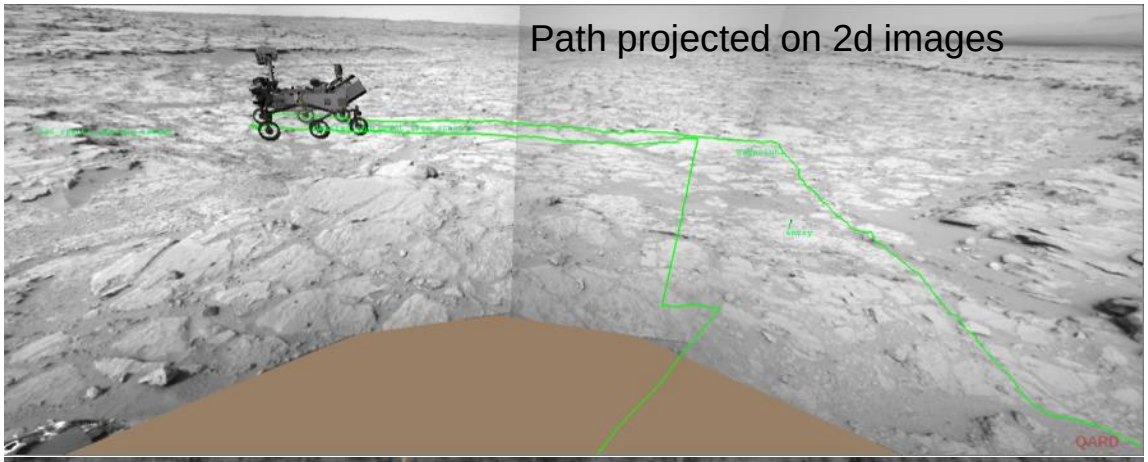
TELEMETRY FROM MARS

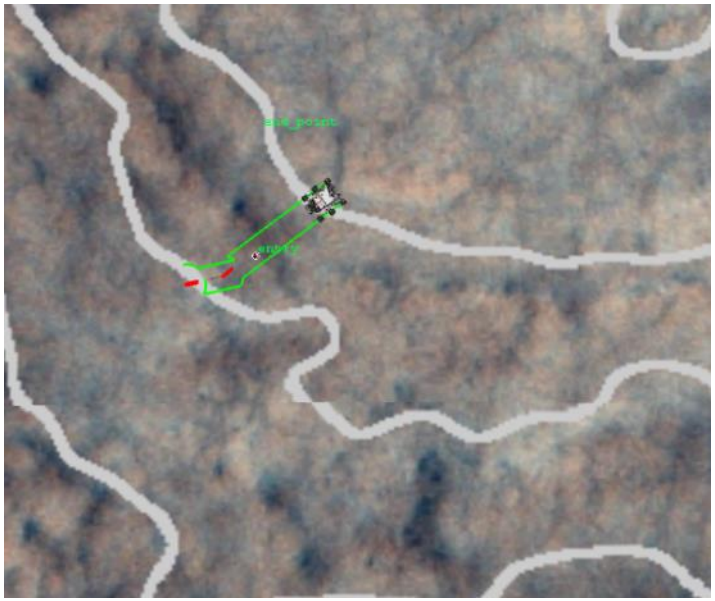
A previous day's images are fed into the Rover Simulation Visualization Program (RSVP) and 3D meshes are created.

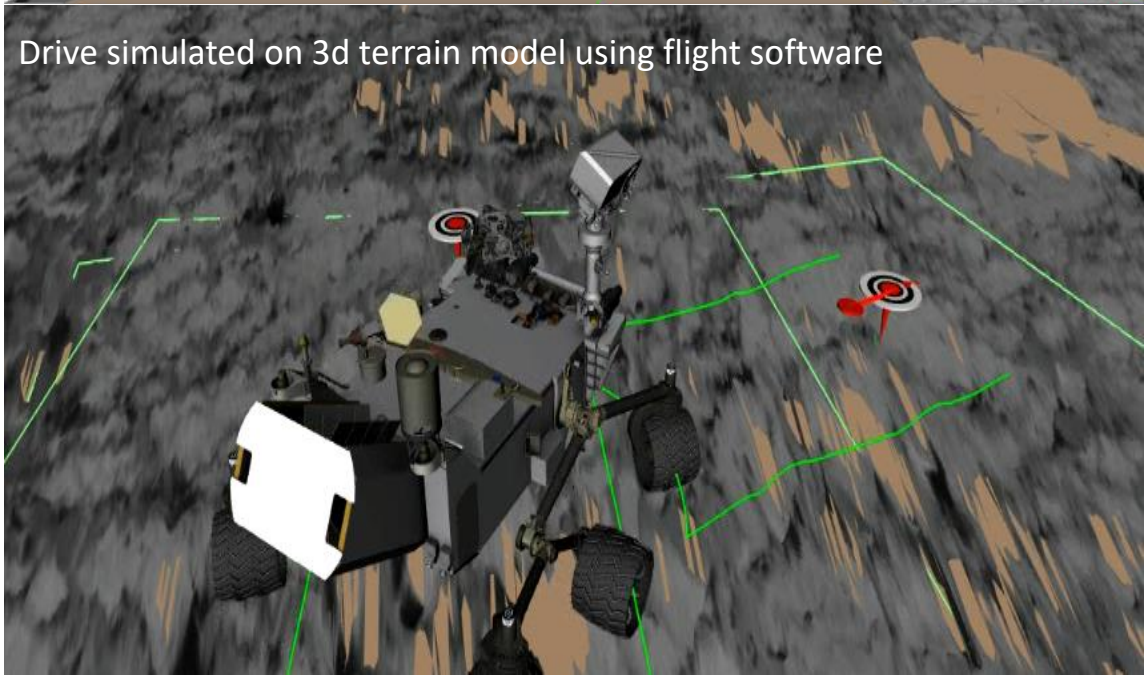


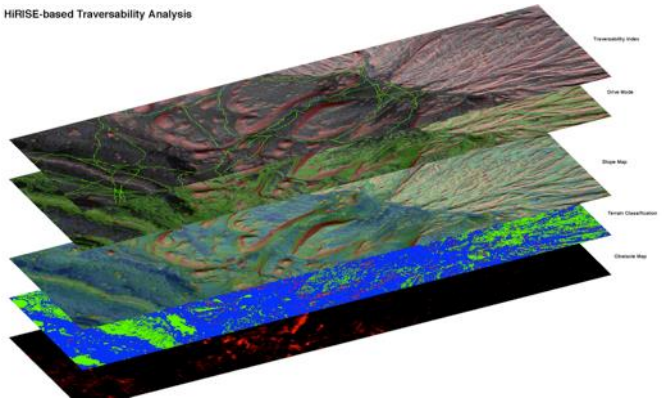
Rover drivers wear shuttered 3D goggles to view stereo imagery and 3D meshes

SEQUENCING AND VALIDATING DRIVE



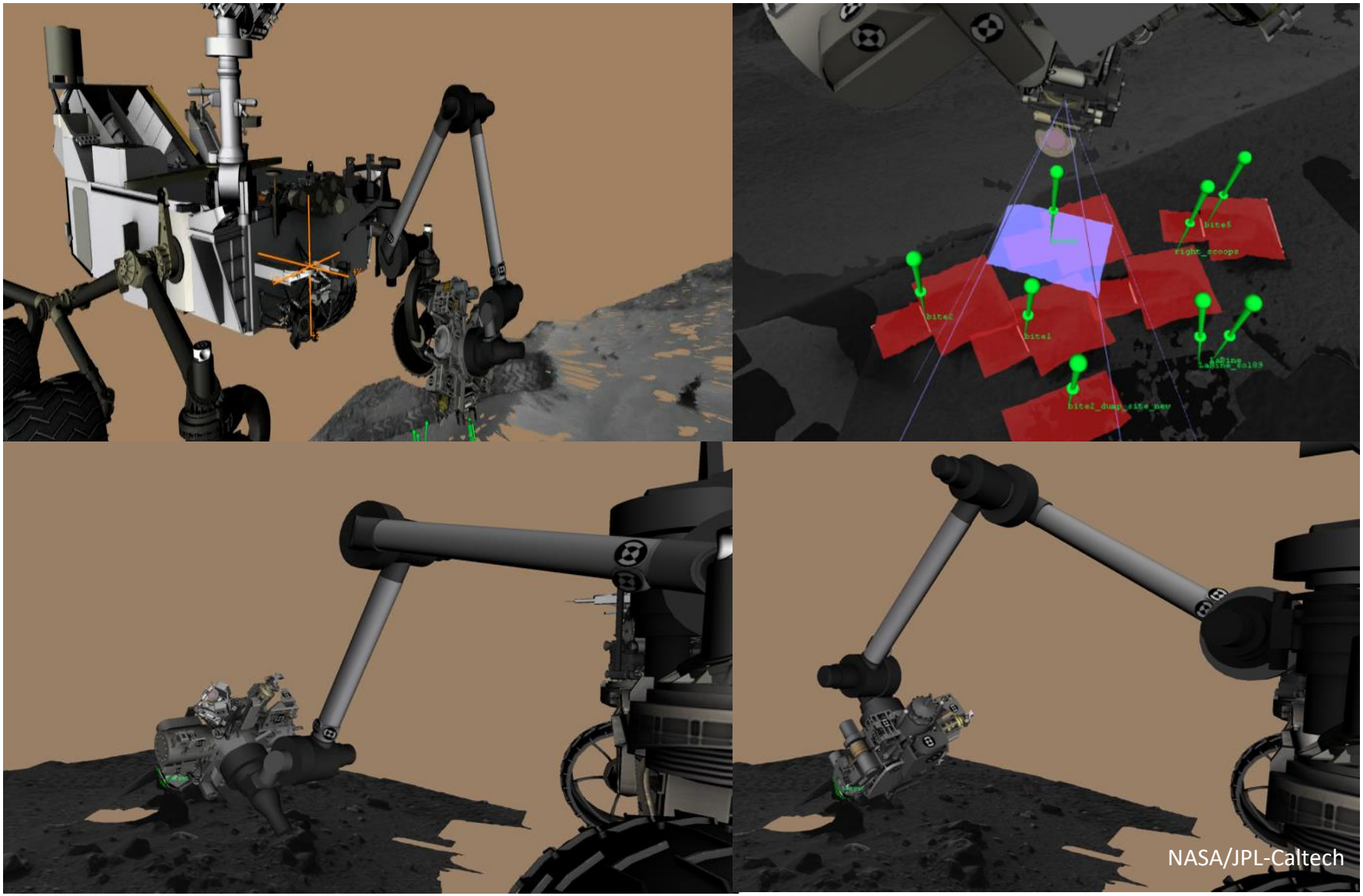




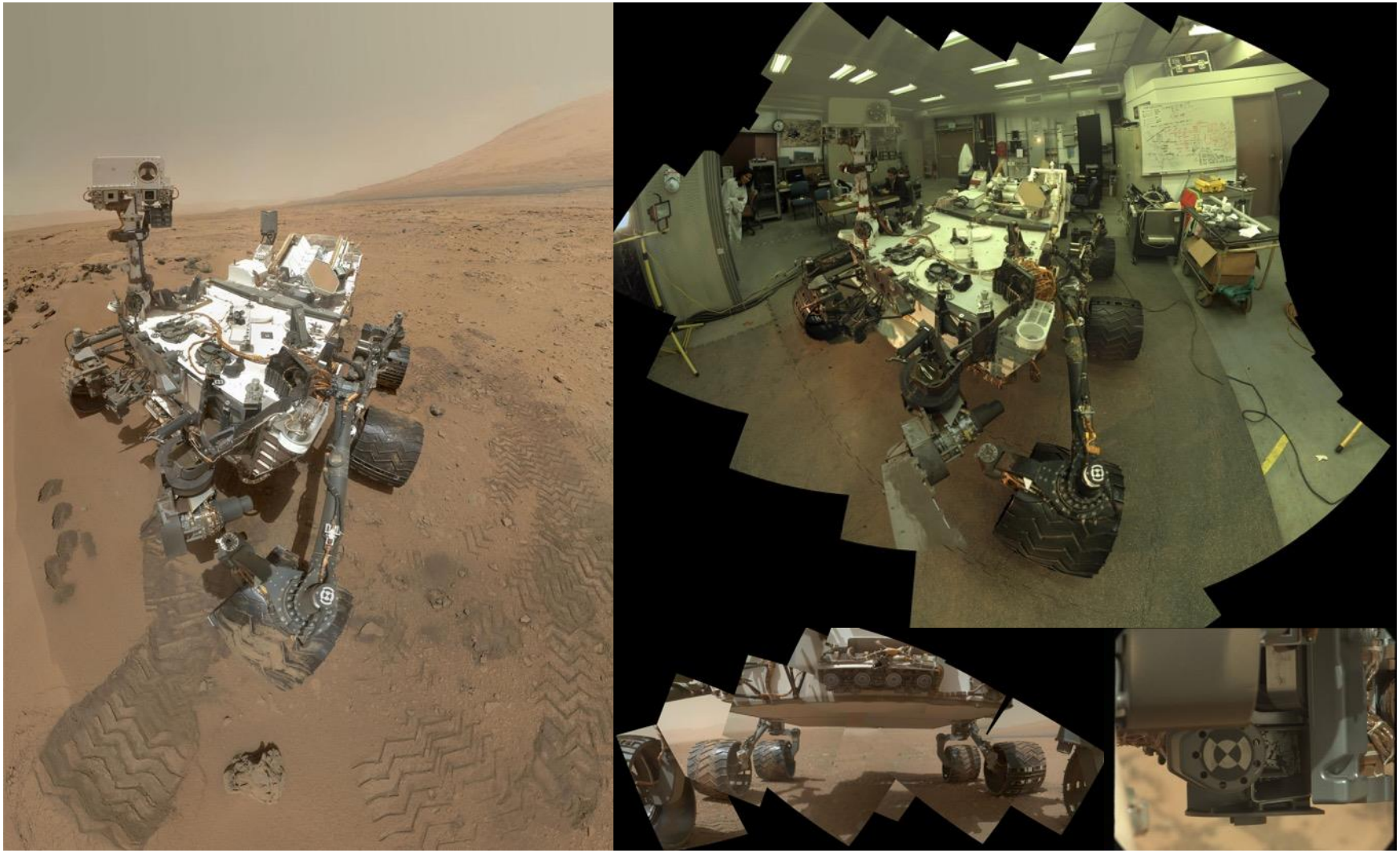


NASA/JPL-Caltech

SEQUENCING AND VALIDATING ROBOTIC ARM MOTION



ROVER SELF INSPECTION



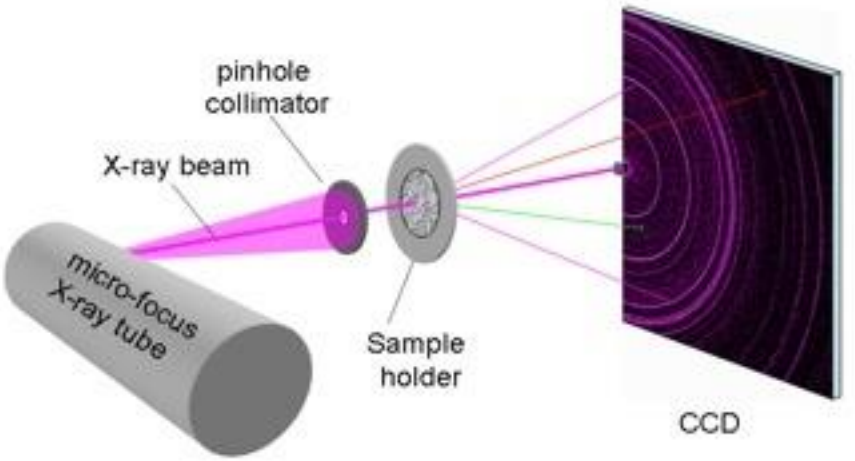
NASA/JPL-Caltech/MSSS

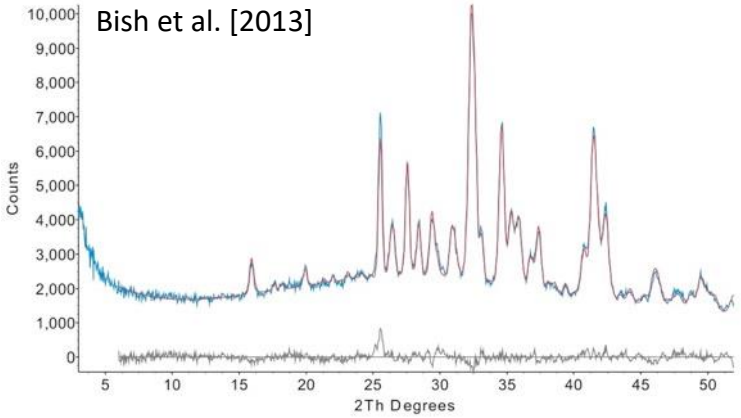
ROVER SELF INSPECTION

https://mars.nasa.gov/msl/multimedia/videos/?v=108

NASA/JPL-Caltech

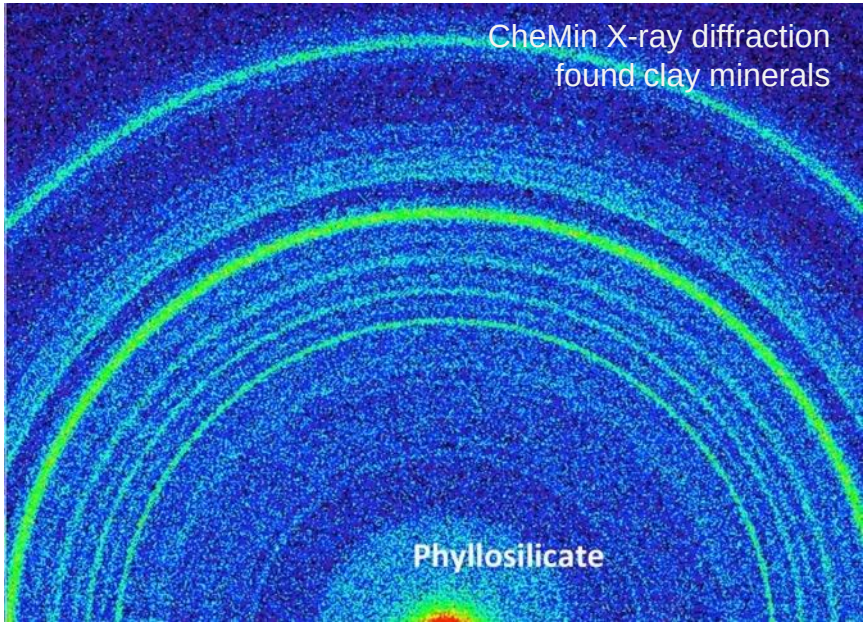
CHEMIN USES X-RAYS TO IDENTIFY MINERALS



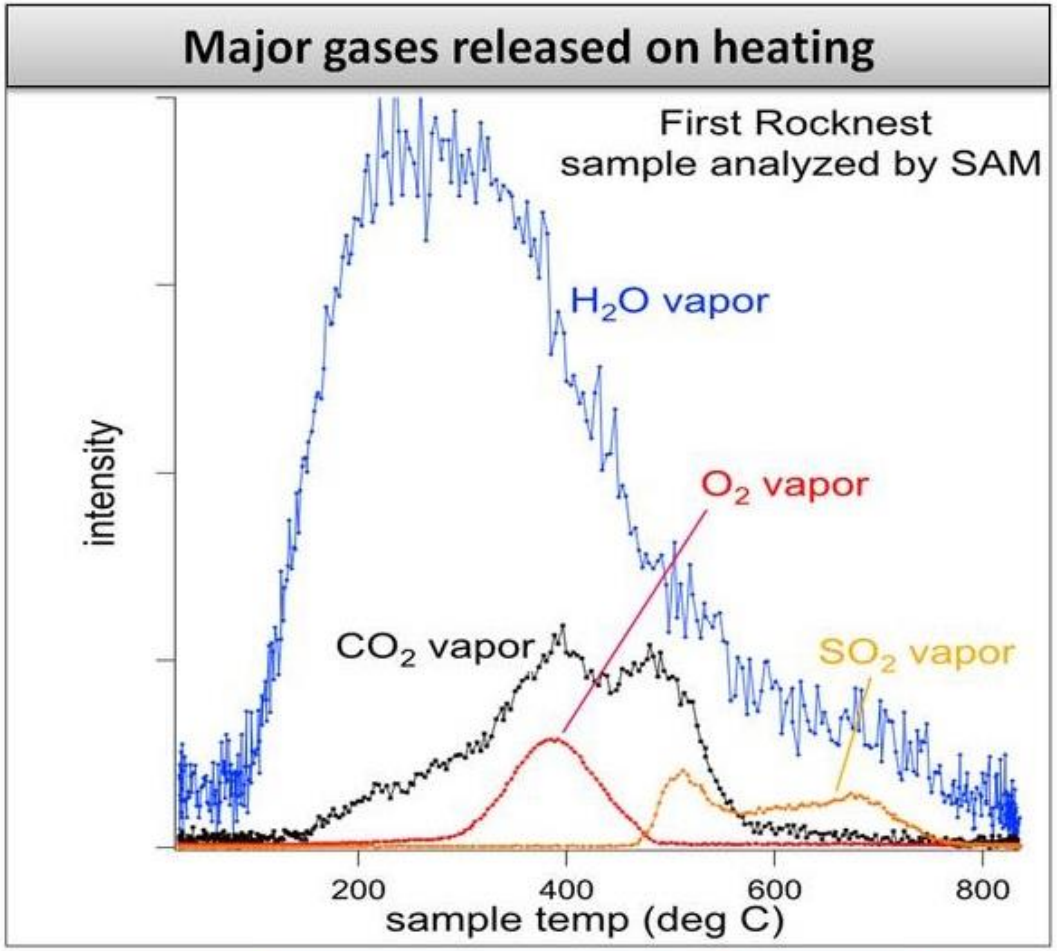


Rocknest sand has a typical Mars basalt composition, but also 1.5-3% bound water

At Yellowknife Bay, Curiosity ifound an ancient lake, the key chemical ingredients required by life (such as carbon, nitrates, and sulfur), and chemical energy usable for microbial metabolism



SAM IS A MASS SPECTROMETER, GAS CHROMATOGRAPH, AND TUNABLE LASER SPECTROMETER



Water

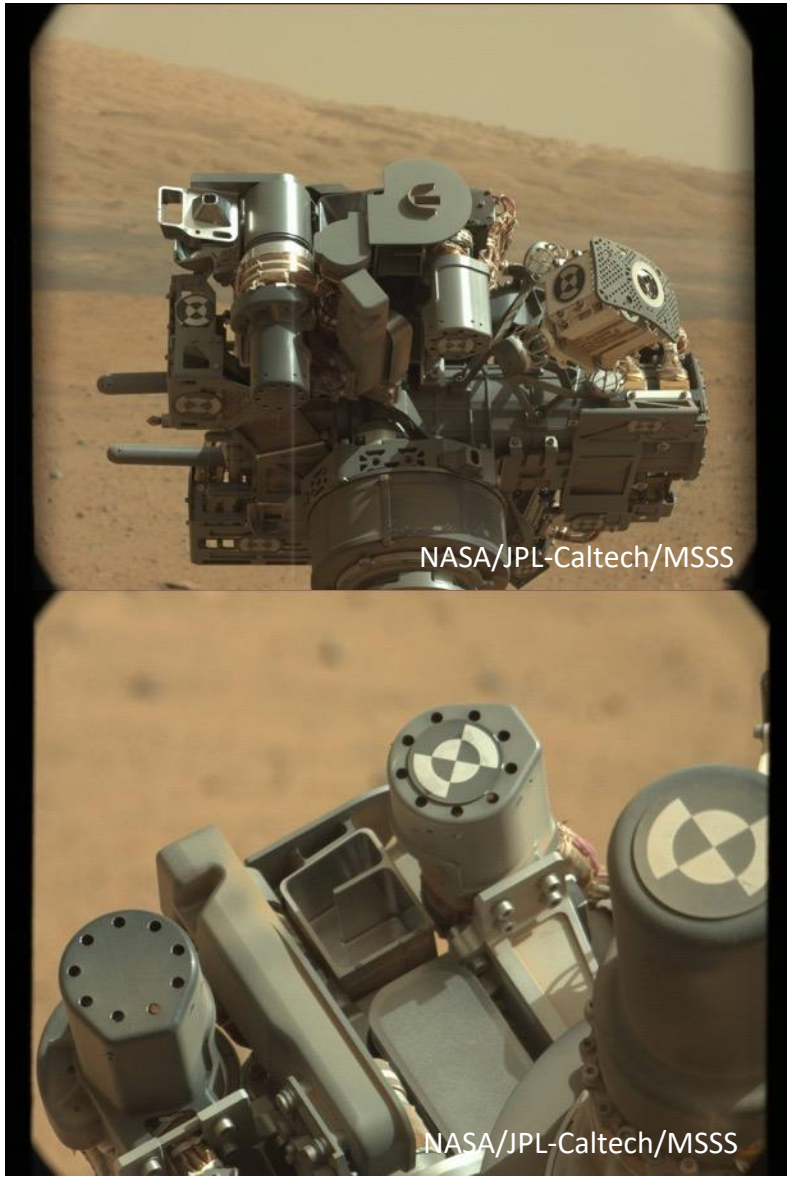
Oxygen

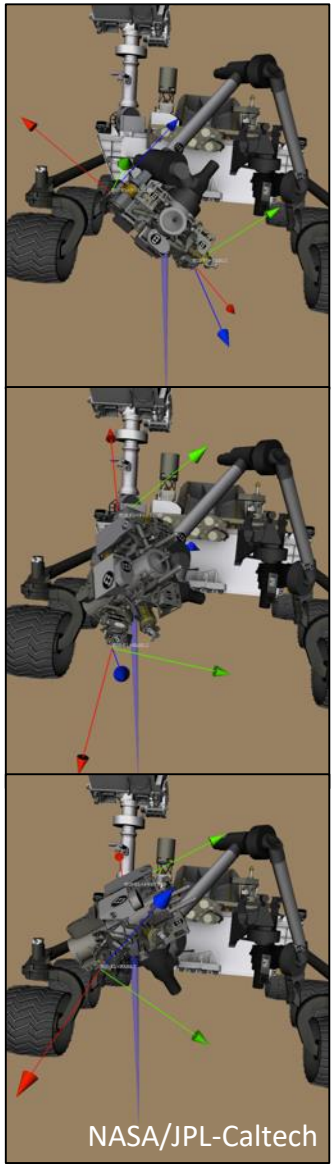
Sulfate

Hot → Hotter

SAM found evidence for water, sulfate minerals, Fe/Mg carbonates, and chlorate/perchlorate compounds

CACHED SAMPLE





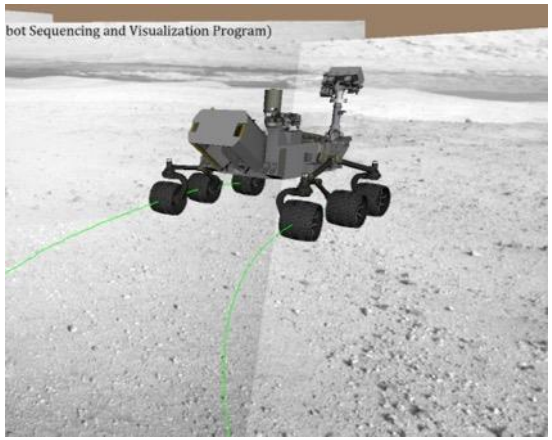
ROBOTICS AND AUTONOMY TECHNOLOGY

- Velocity-controlled Driving
- Autonomous Fault Response
- Visual Odometry
- Dense Stereo Vision
- Autonomous Terrain Assessment
- Local and Global Waypoint Planning
- Multi-sol Driving
- Visual Target Tracking
- Precision Arm Placement
- Percussive Drill
- Cached Sample Manipulation
- Simulation
- Rover Sequencing and Visualization
- Autonomous Laser Spectrometer Science Target Selection
- Traction Control

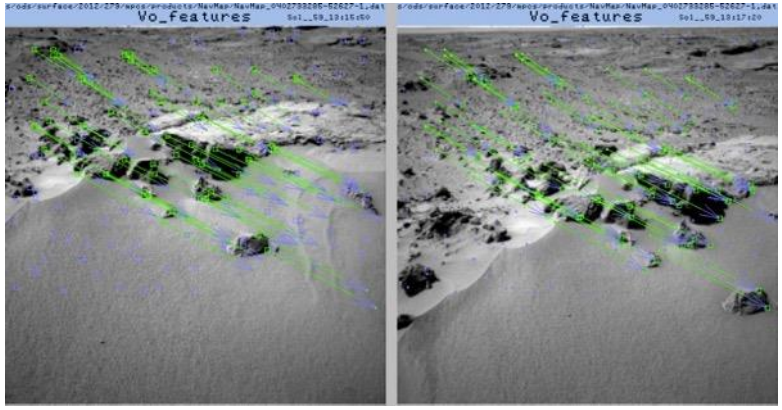
SOFTWARE RESOURCES

	Mars Exploration Rovers	Mars Science Laboratory
Radiation-hardened CPU	RAD6000 (Power PC)	RAD750 (Power PC)
Clock Speed	20 MHz	133 Mhz
On-board RAM	128 Mbytes	128 Mbytes
Real Time Operating System	VxWorks 5.3.1	VxWorks 6.7
Addressable Code RAM	32 Mbytes	32 Mbytes
FSW + ROTS Code Size	10 Mbytes	21 Mbytes
Additional RAM	n/a	512 Mbytes SDRAM (half of RAMFS)
Per-Task Memory access	Shared Memory	Shared Memory
C/Embedded compiler	Green Hills MULTI 3.5	GCC 4.1.2

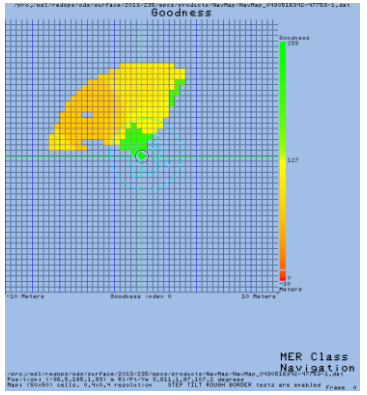
VARIABLE AUTONOMY FOR DRIVING



Directed driving



Visual odometry, or
Slip Check + “Auto”



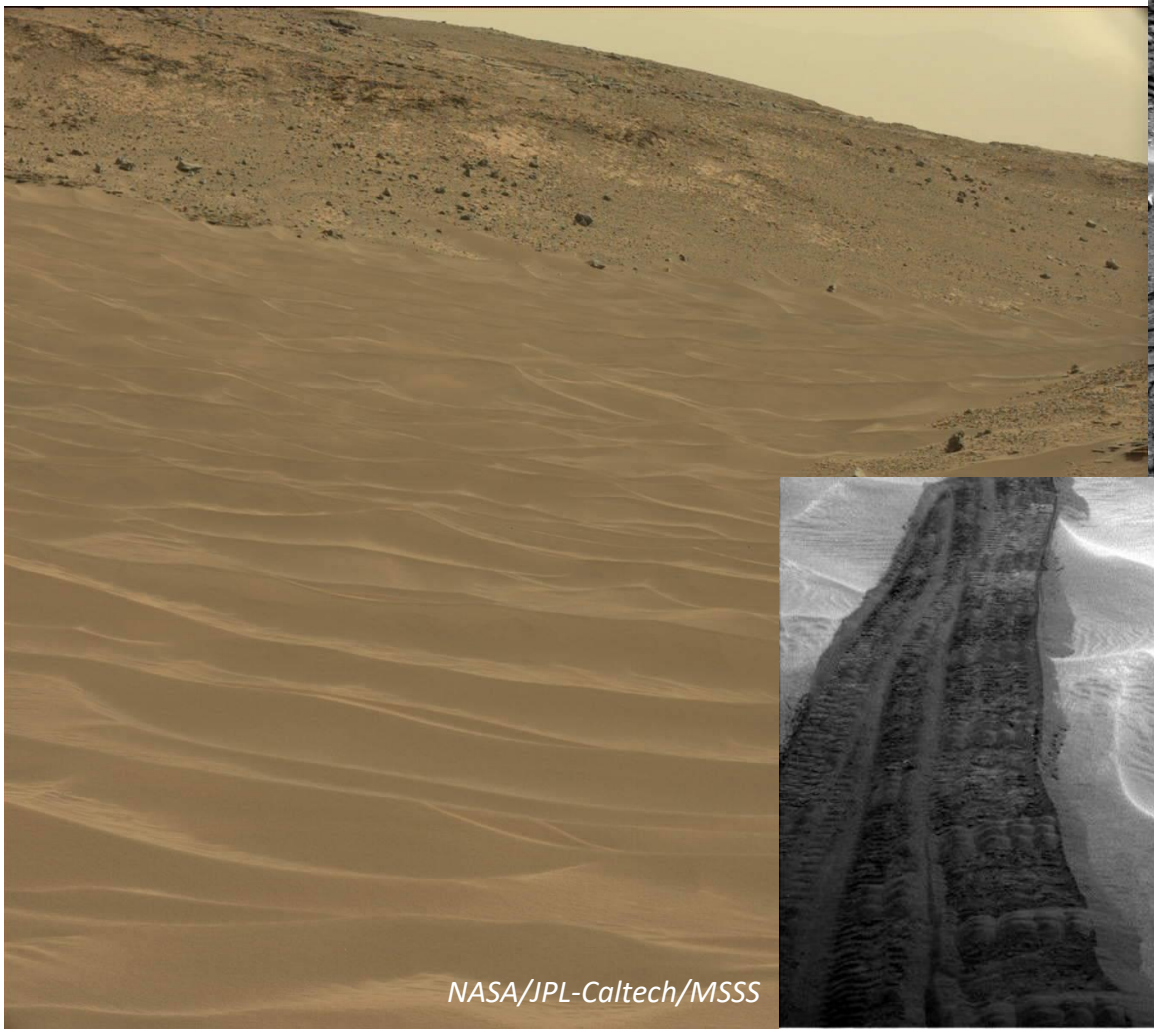
Auto-navigation;
Geometric Hazard
Detection and Avoidance

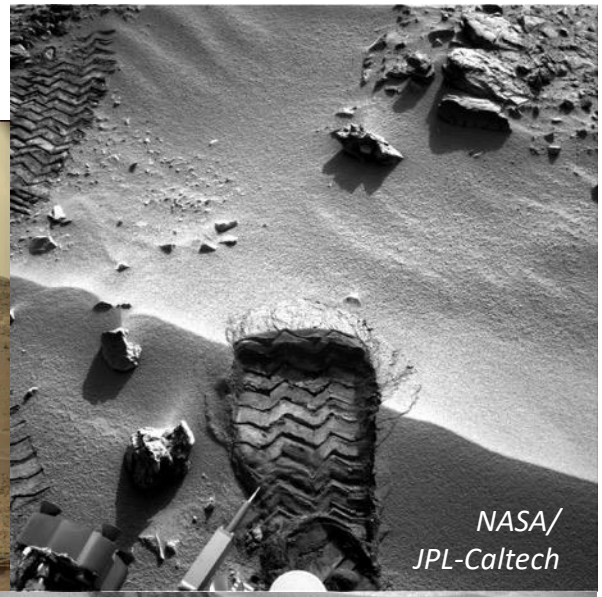
NASA/JPL-Caltech

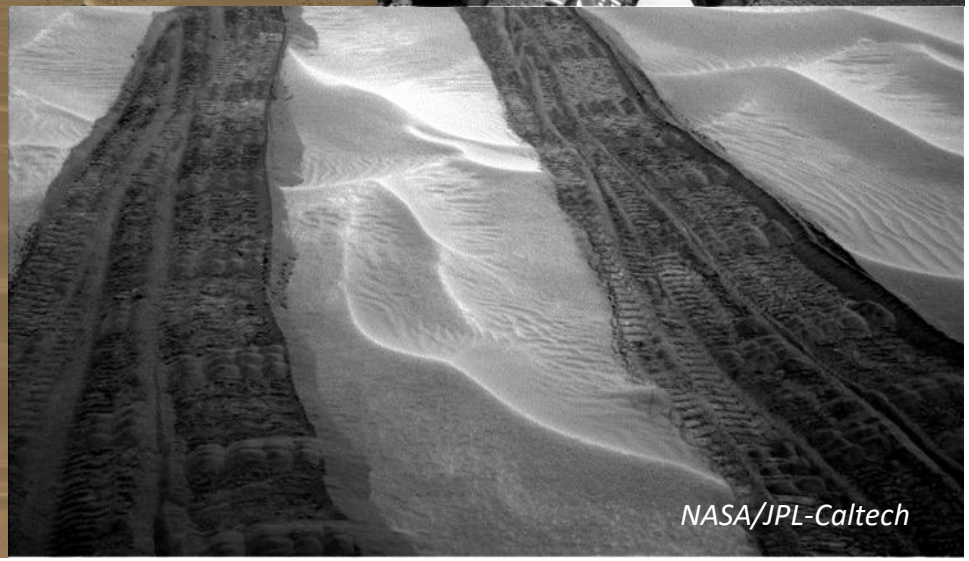
DIRECTED DRIVING

https://mars.nasa.gov/msl/multimedia/videos/?v=79

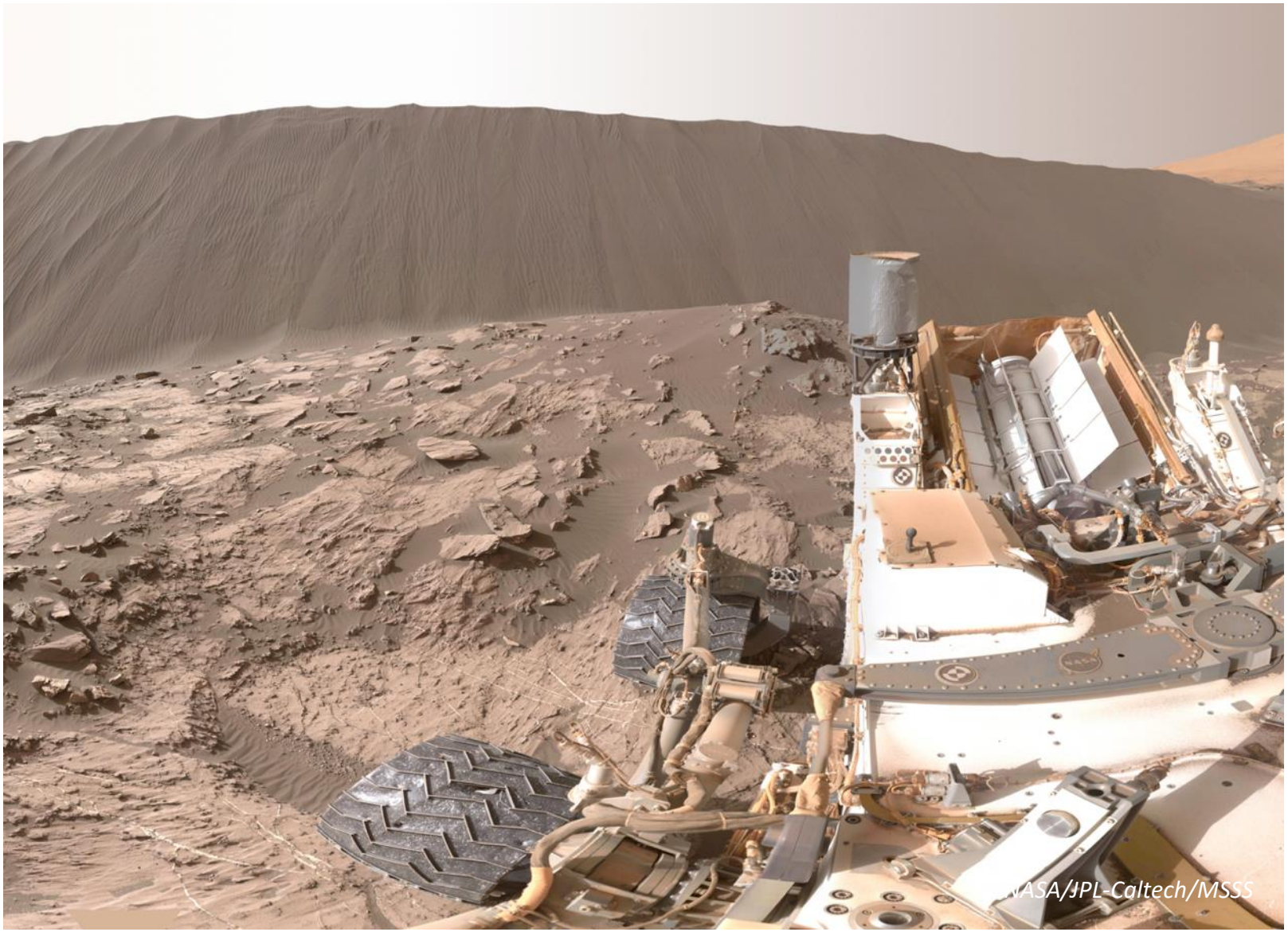
VISUAL ODOMETRY



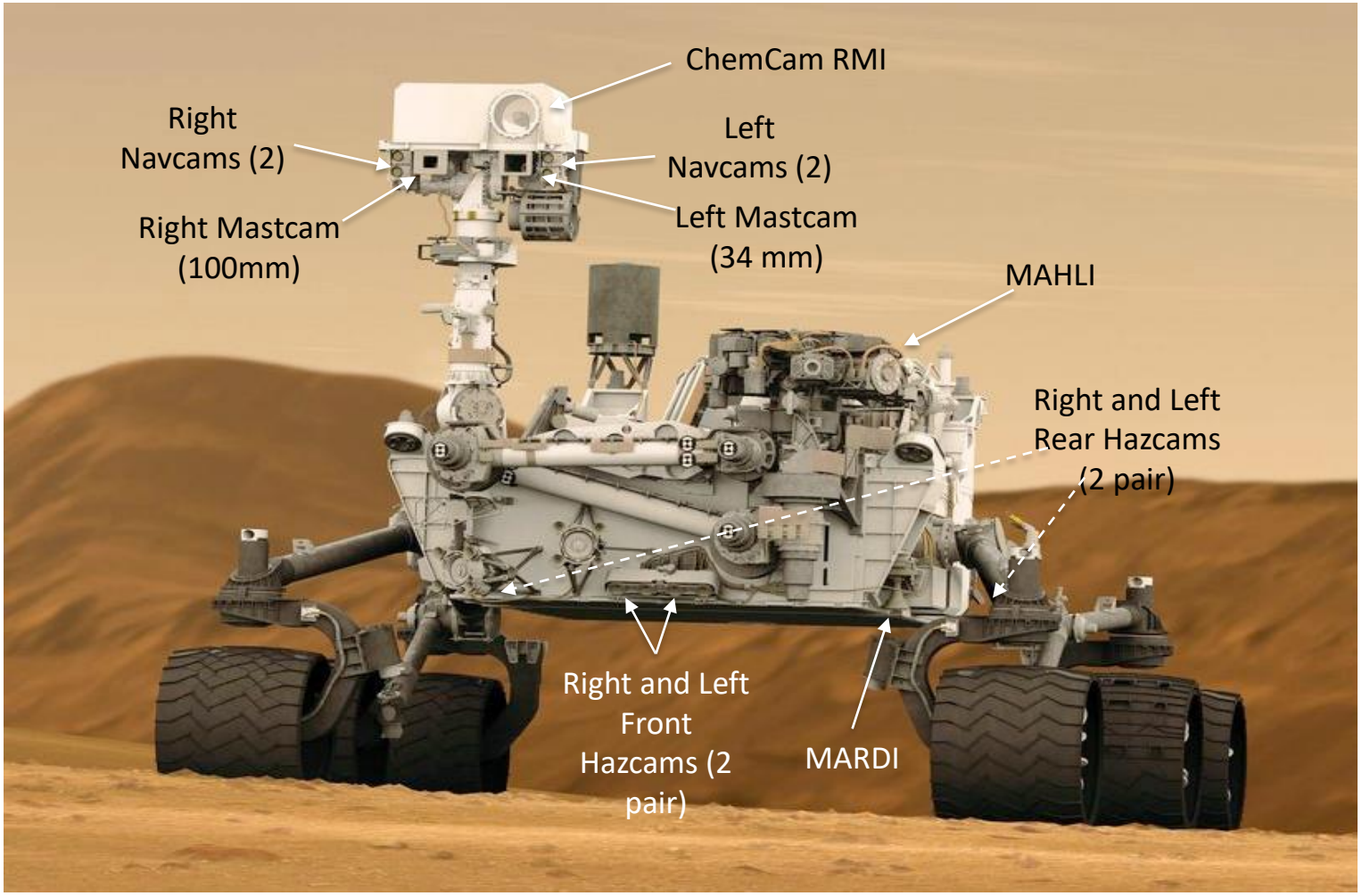




VISUAL ODOMETRY

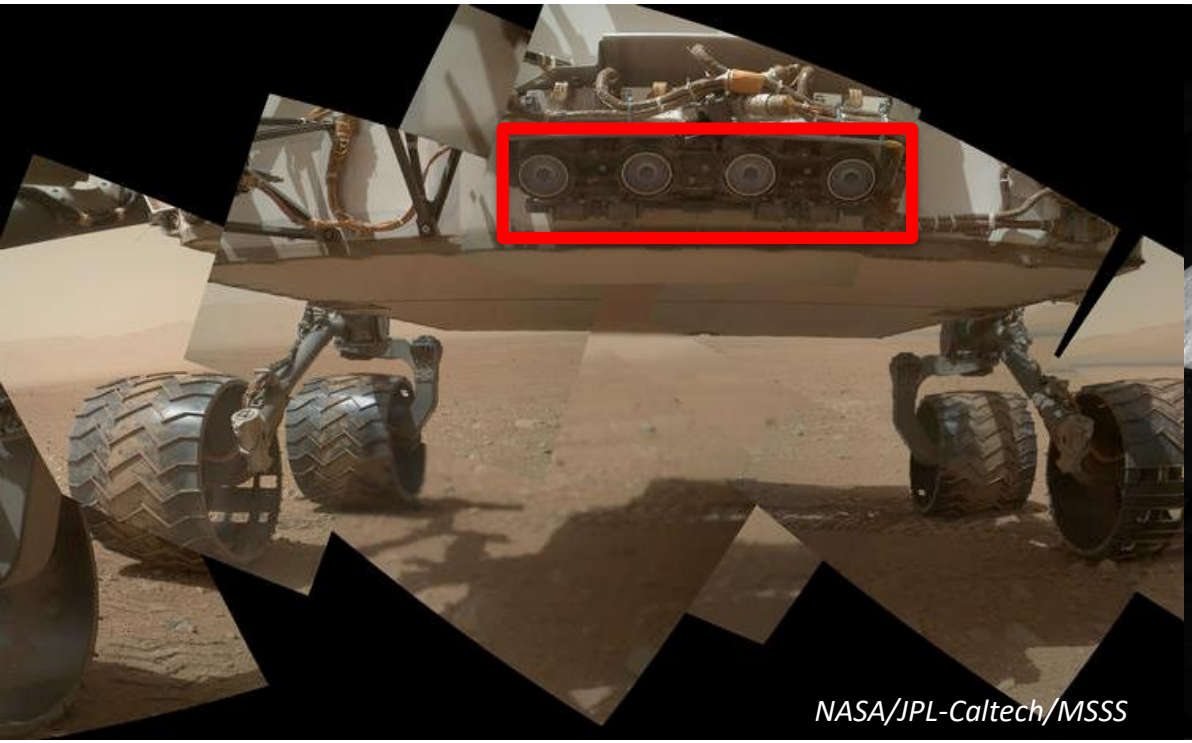


17 CAMERAS


ChemCam RMI
Right Navcams (2)
Left Navcams (2)
Right Mastcam (100mm)
Left Mastcam (34 mm)
MAHLI
Right and Left Rear Hazcams (2 pair)
Right and Left Front Hazcams (2 pair)
MARDI

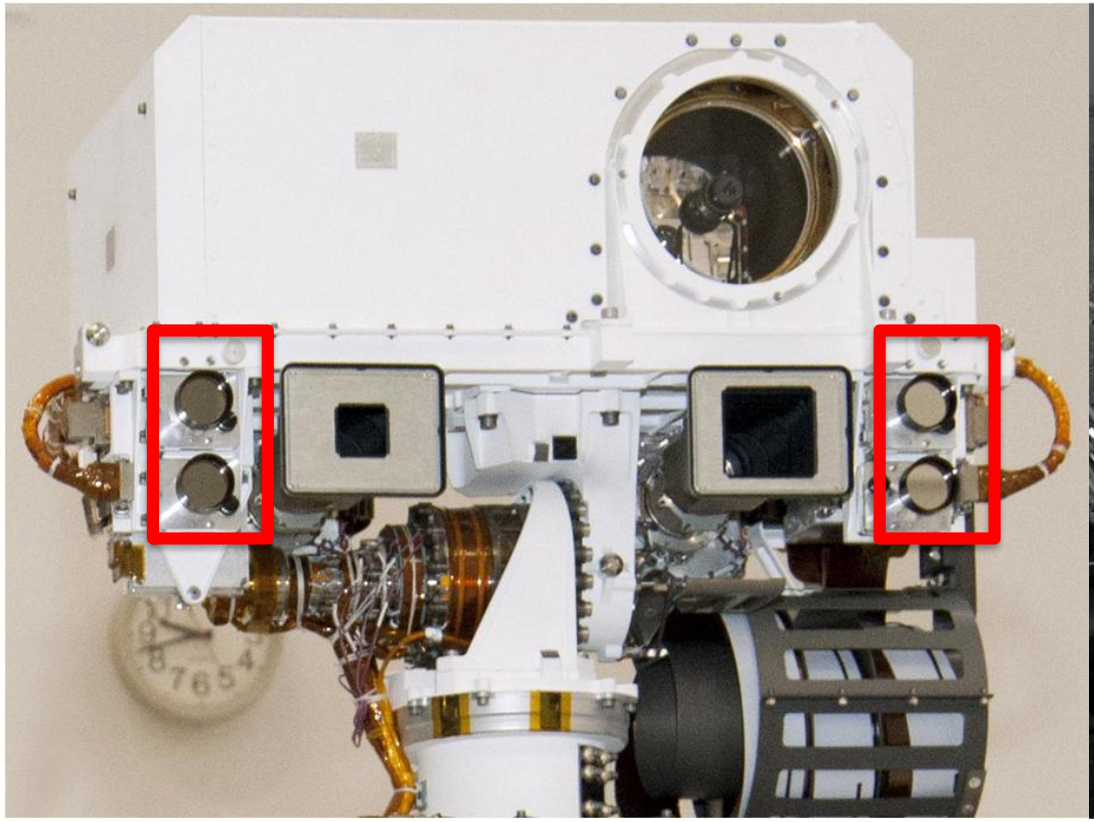
HAZARD AVOIDANCE CAMERAS

120^{o} wide angle view of the area near the rover. Front cameras have 16cm baseline, rear cameras have 10cm baseline



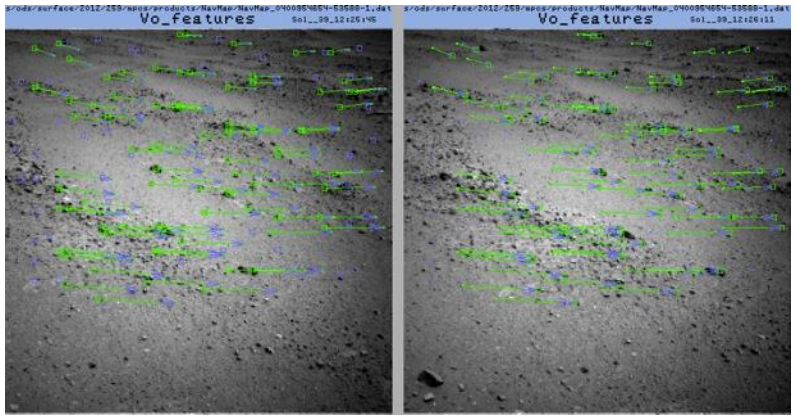
NAVIGATION CAMERAS

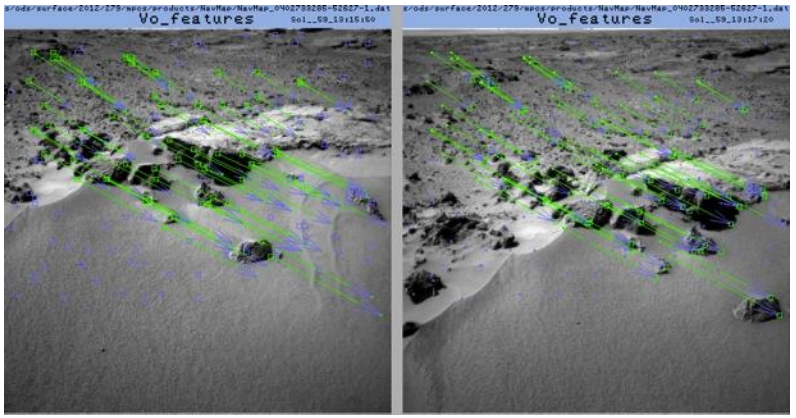
45^{o} field of view 7 feet off the ground with 42cm baseline

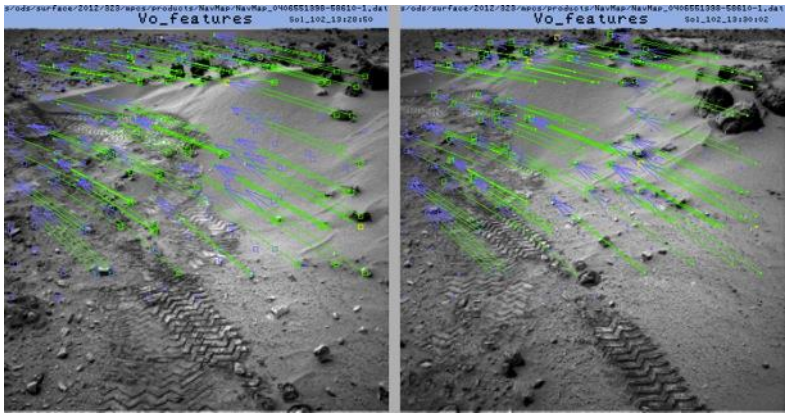


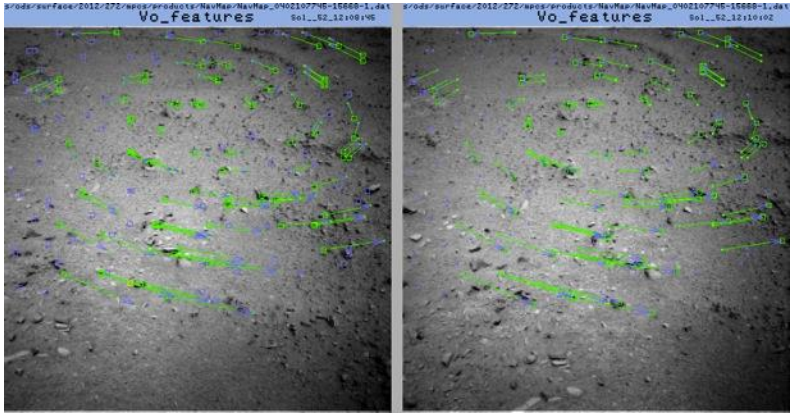
NASA/JPL-Caltech

VISUAL ODOMETRY









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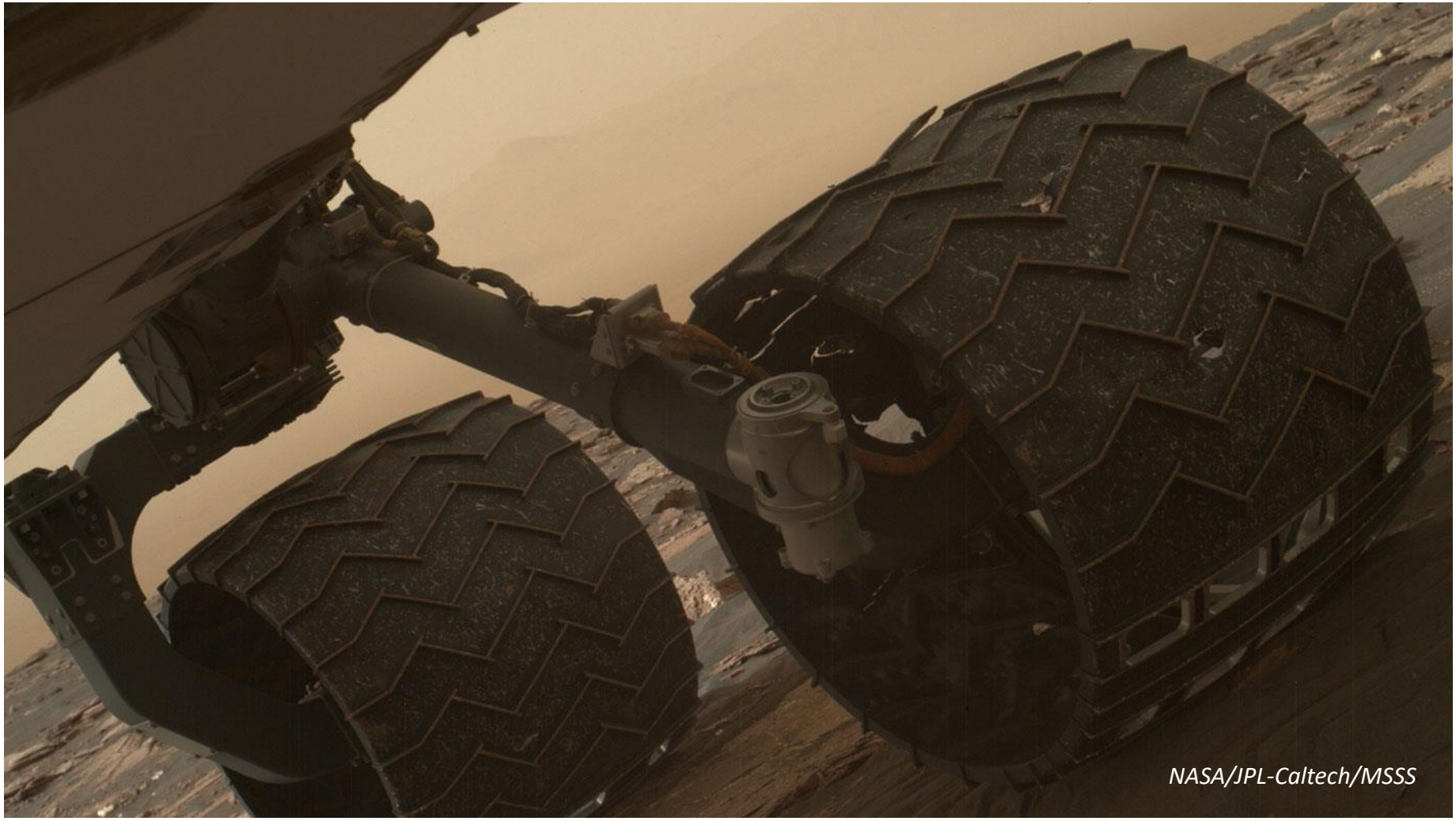
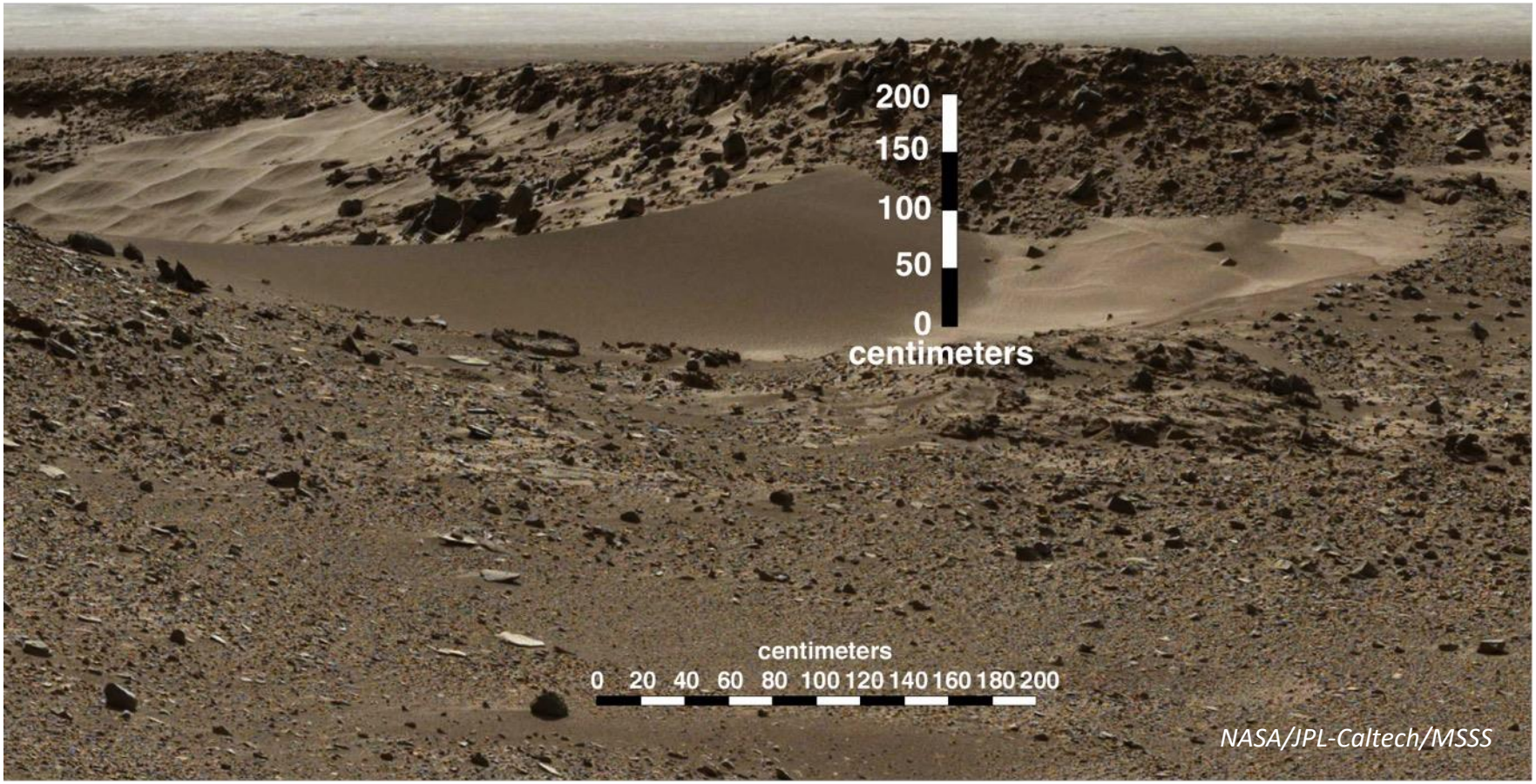
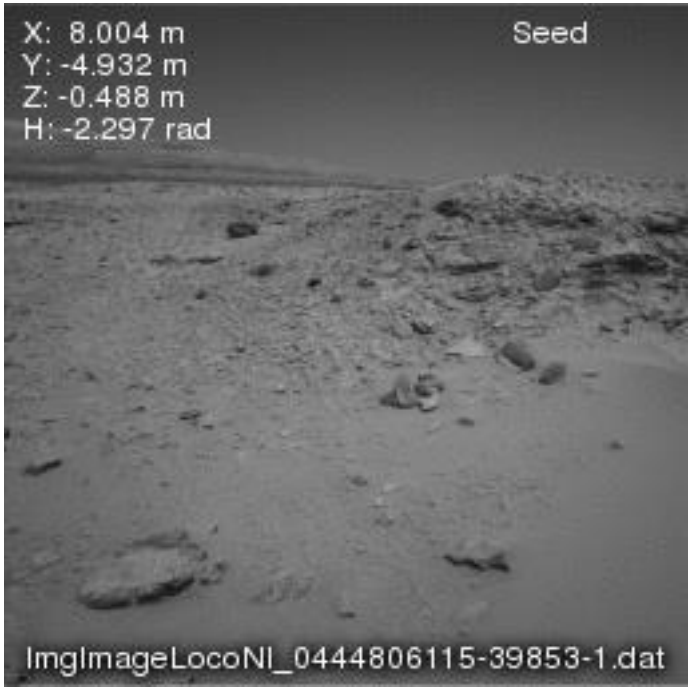
WHEEL WEAR



DINGO GAP


200
150
100
50
0
centimeters
centimeters
0 20 40 60 80 100 120 140 160 180 200
NASA/JPL-Caltech/MSSS

ROVER SLIP

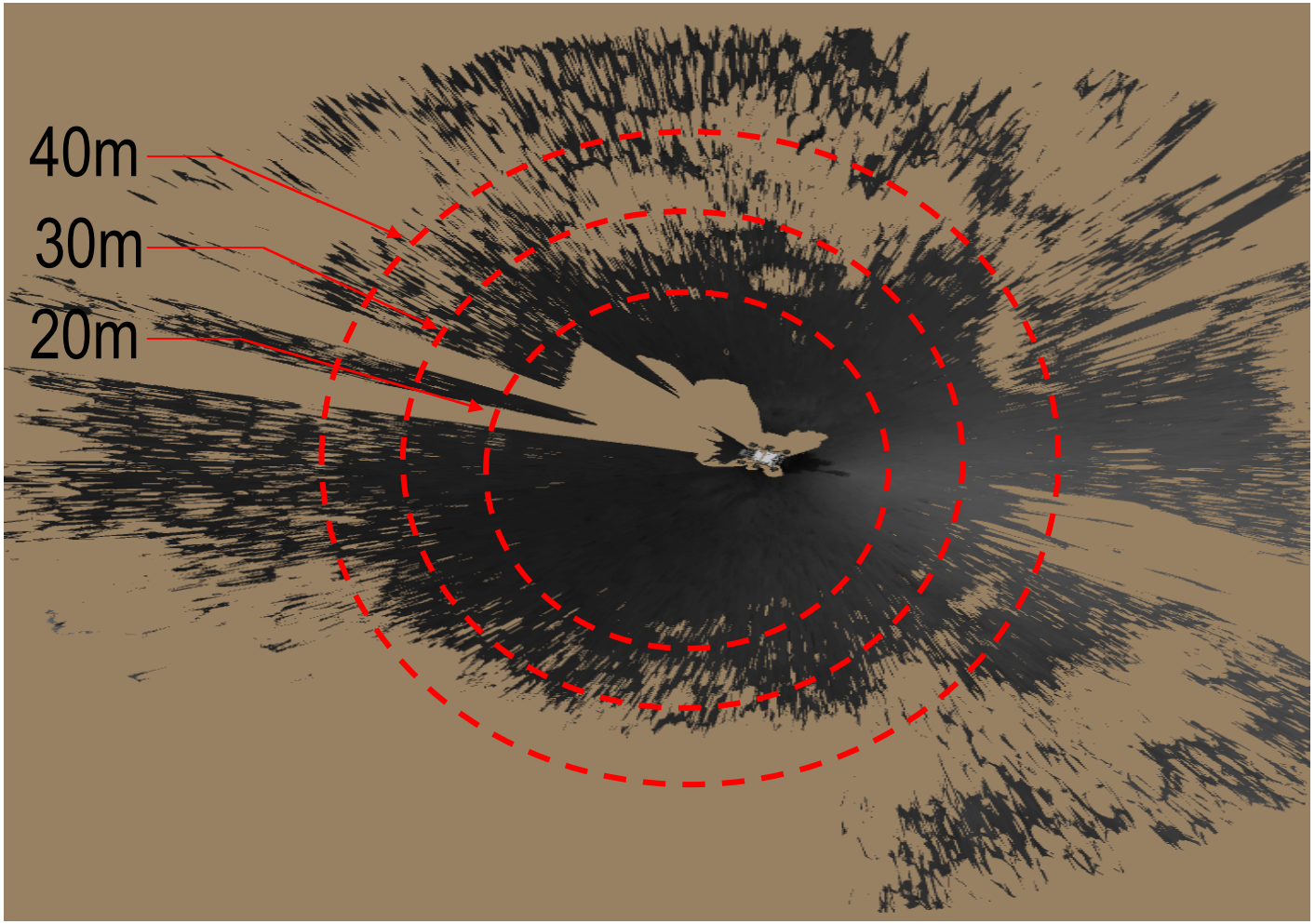


NASA/JPL-Caltech

ROVER SLIP

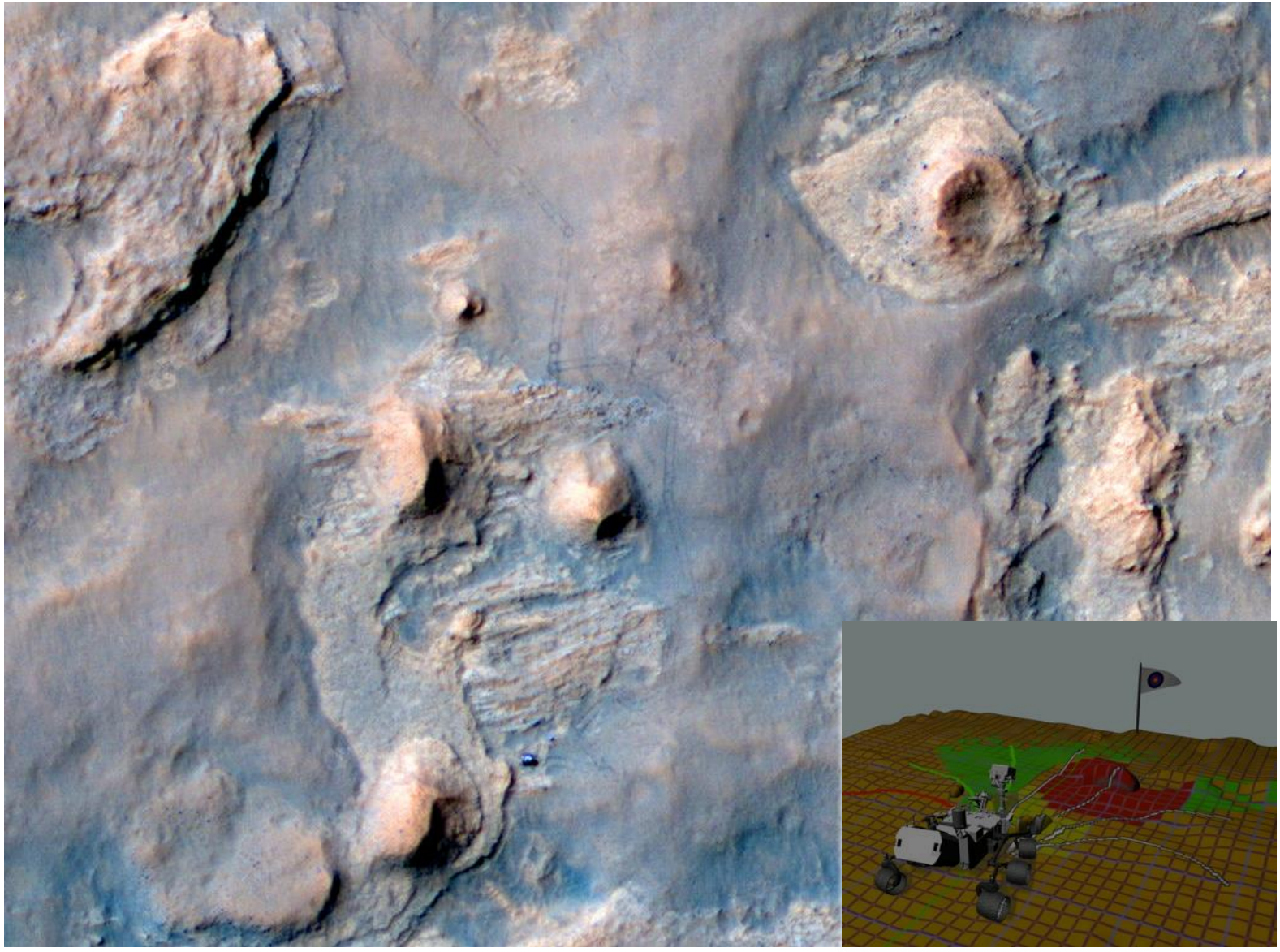
NASA/JPL-Caltech

DETAIL THE NAVCAM CAMERAS CAN TYPICALLY SEE NEARBY



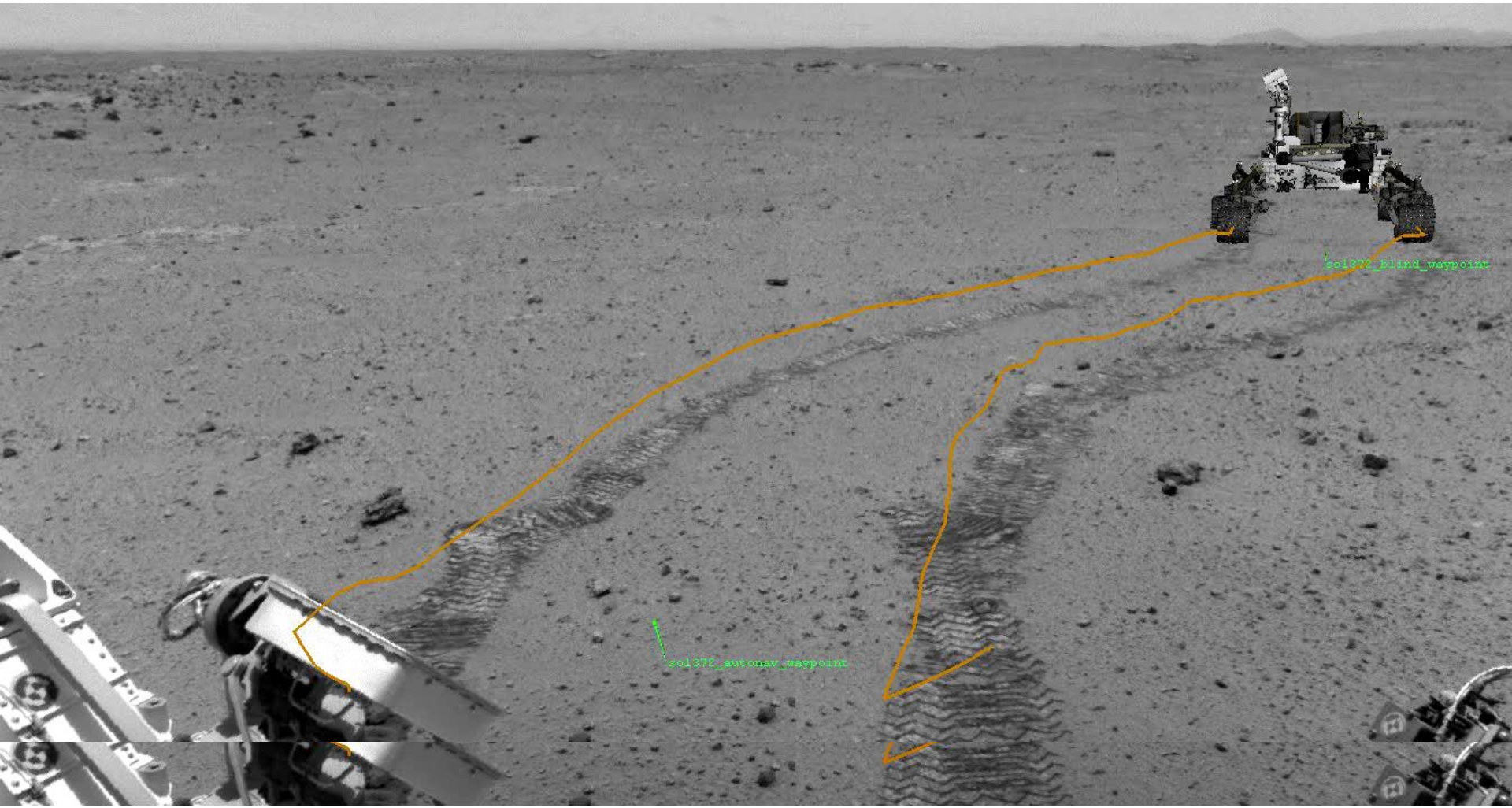
3D data from Navcam stereo is often supplemented by color texture information in Mastcam images

TERRAIN ANALYSIS



NASA/JPL-Caltech

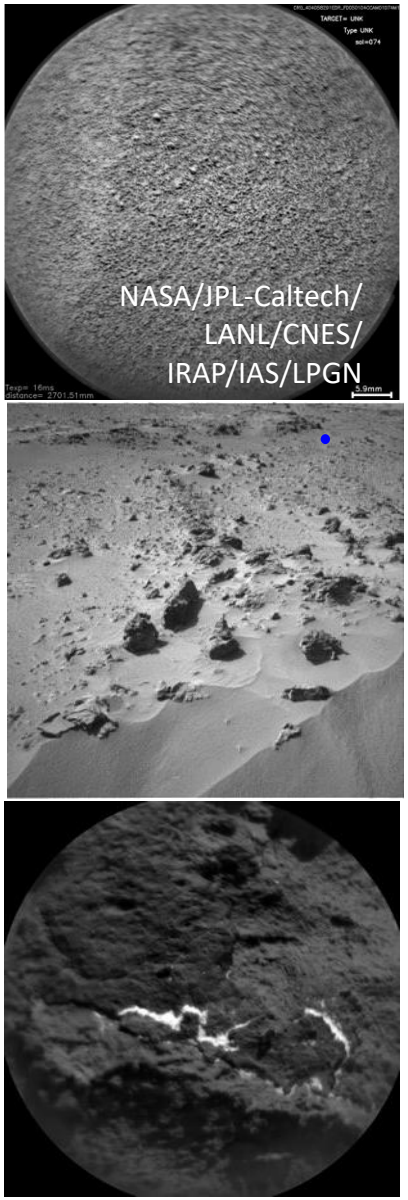
AUTONAV



NASA/JPL-Caltech

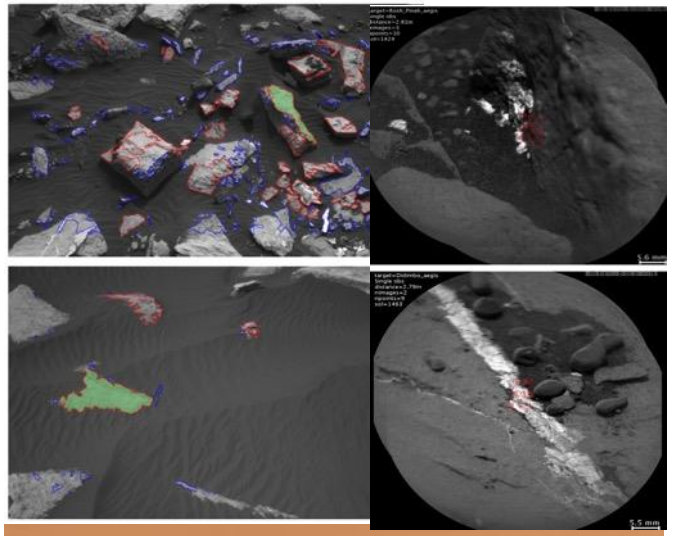
AUTONOMOUS LASER SPECTROMETER TARGETING

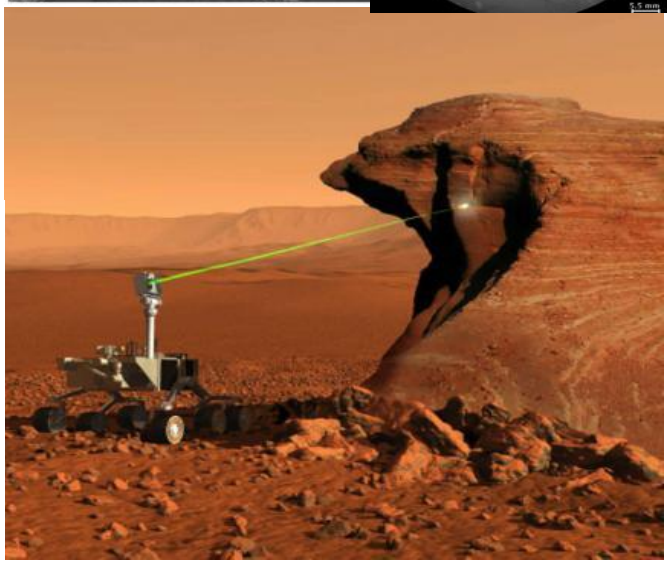
- Chemcam is a Laser-Induced Breakdown Spectrometer (LIBS) located on rover mast
  - Samples rocks from a distance of 1 to 7 meters
    Vaporizes small portion of rock and collects light spectrum that is emitted
  - Able to rapidly identify rock elemental compisiton
- Autonomous targeting enables ChemCam measurements to be taken at different times of day without waiting for Earth
- Analyze wide angle Navigation camera or narrow angle Remote Micro Images

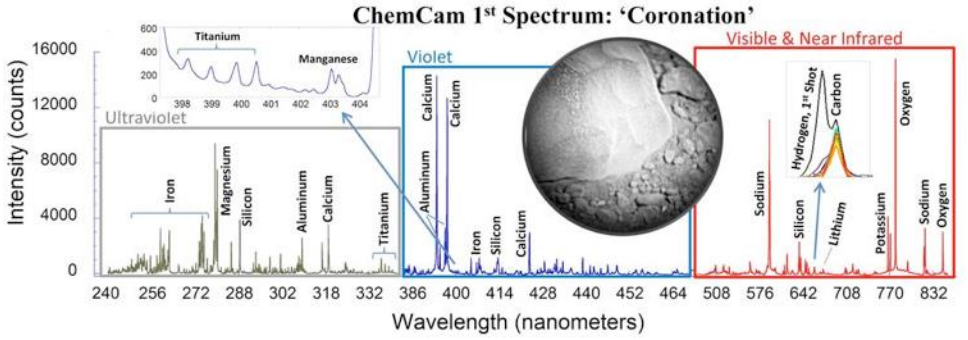


AUTONOMOUS SCIENCE

- AEGIS Automated Targeting System
- Provides intelligent targeting and data acquisition by
  - analyzing images of the rover scene
  - identifying high-priority science targets (e.g., rocks), and
  - taking high quality data of these targets by setting frame for new instrument pointing
- Operational on Curiosity and Opportunity Rovers

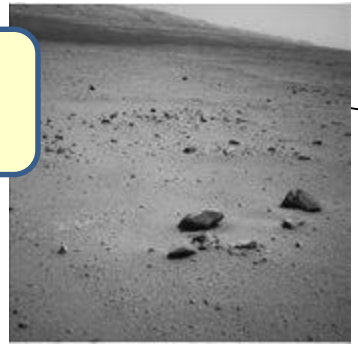






ONBOARD PROCESS

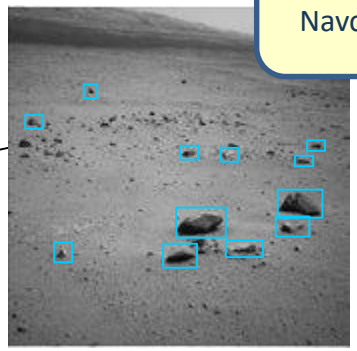
Image pointing determined by ground.



Navcam or RMI acquisition

Target detection

Detection of rock candidates in Navcam image.

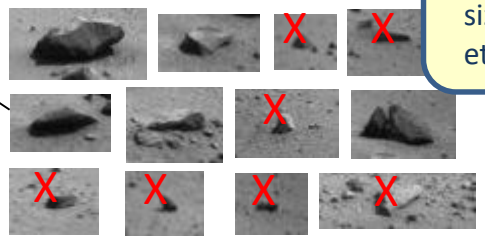


Quantification of key target properties such as intensity, size, shape, and distance from rover.

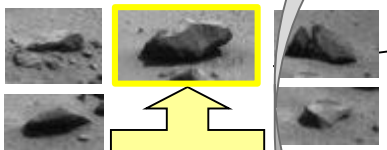
Target feature extraction

Target filtering

Ops can filter targets based on size, distance, etc.



Ops can prioritize important properties for each run



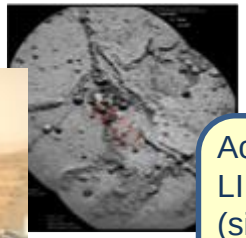
Top score for large size

Target prioritization

Set VTT frame to target position

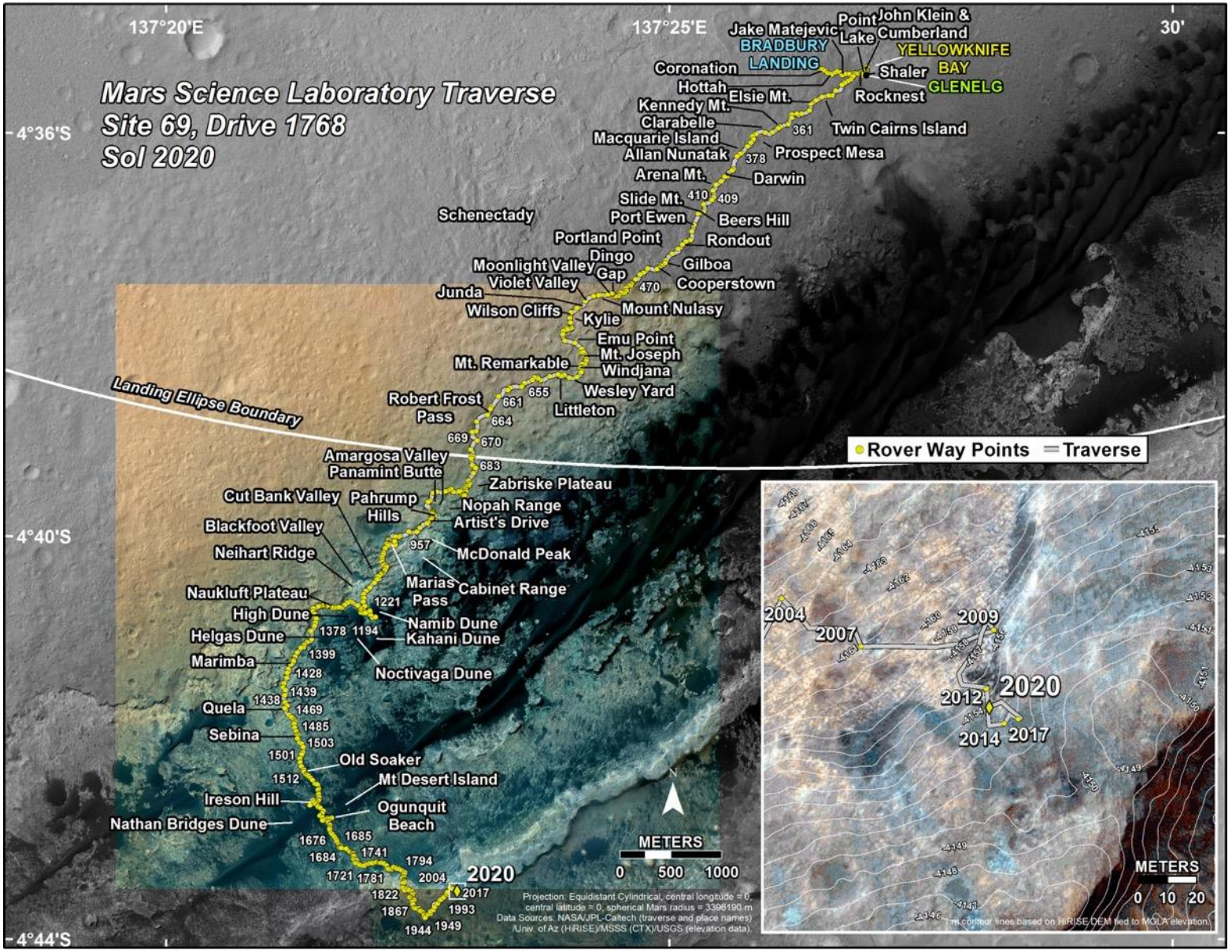
Can repeat for multiple targets

CCAM raster acquired using VTT frame

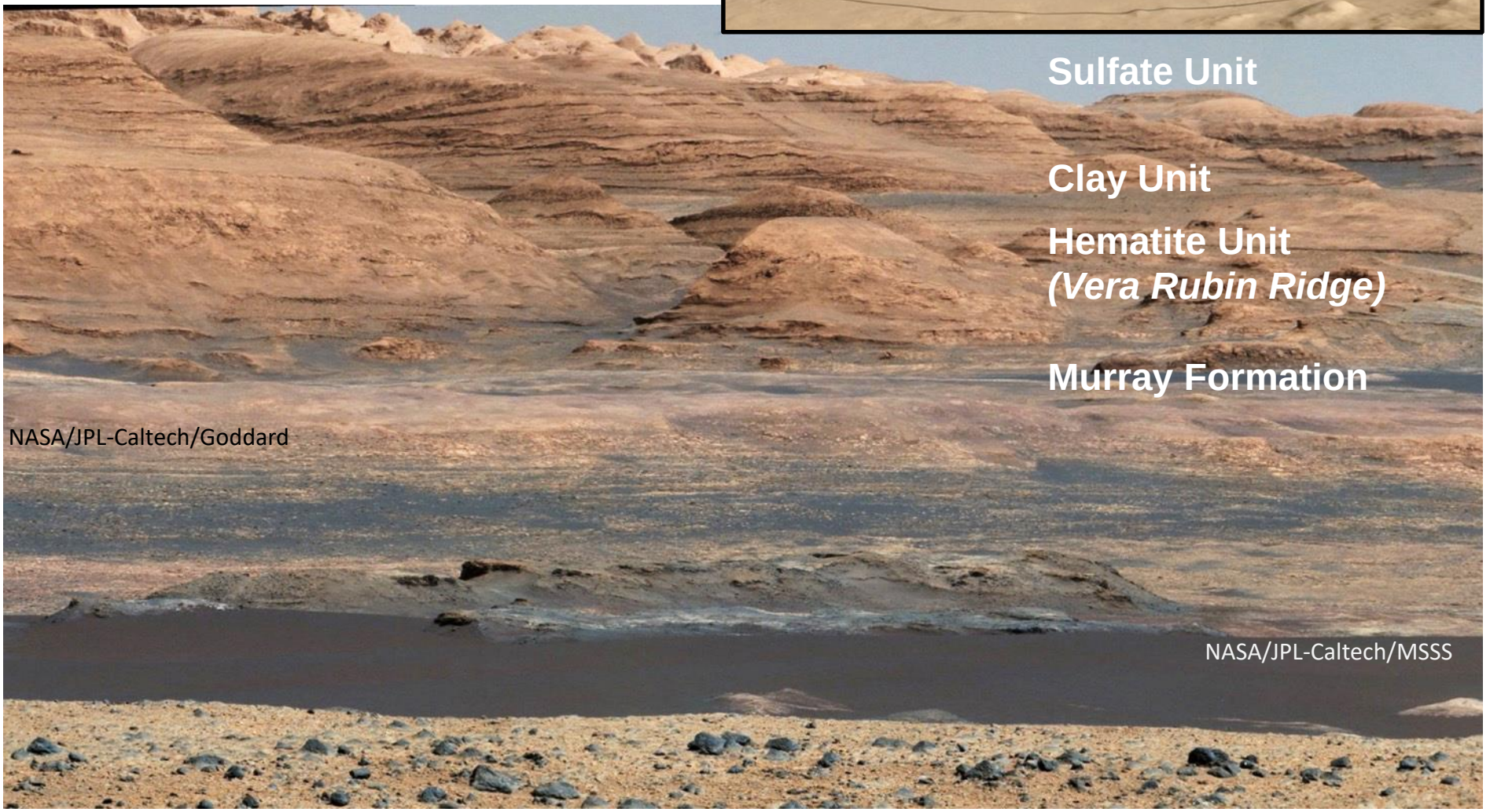


Acquire ChemCam LIBS raster of target (size and direction pre-specified by ground)

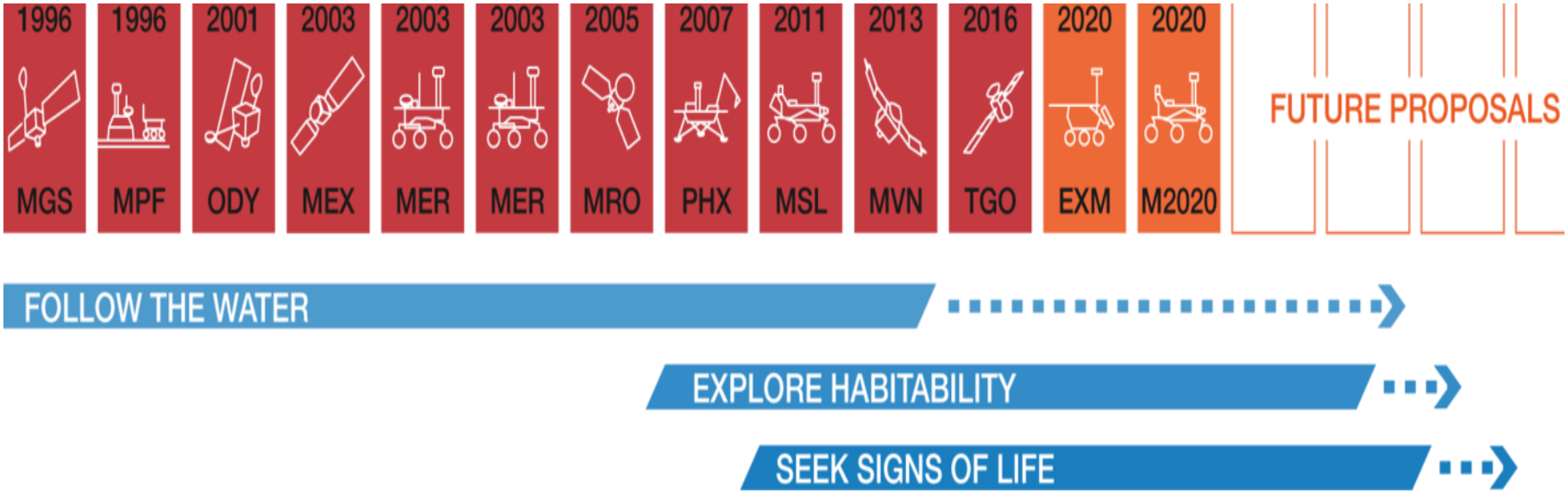
TRAVERSE


Mars Science Laboratory Traverse
Site 69, Drive 1768
Sol 2020
137°20'E
137°25'E
30'
4°36'S
4°40'S
4°44'S
Landing Ellipse Boundary
Rover Way Points
Traverse
Jake Matejevic
Point Lake
John Klein & Cumberland
BRADBURY LANDING
YELLOWKNIFE BAY
GLENELG
Coronation
Hottah
Elsie Mt.
Shaler
Rocknest
Kennedy Mt.
Clarabelle
Macquarie Island
Allan Nunatak
Arena Mt.
Twin Cairns Island
Prospect Mesa
Darwin
Slide Mt.
Schenectady
Port Ewen
Beers Hill
Portland Point
Rondout
Dingo Gap
Gilboa
Moonlight Valley
Violet Valley
Cooperstown
Junda
Wilson Cliffs
Mount Nulasy
Kylie
Emu Point
Mt. Joseph
Mt. Remarkable
Windjana
Wesley Yard
Littleton
Robert Frost Pass
Amargosa Valley
Panamint Butte
Zabriske Plateau
Cut Bank Valley
Pahrump Hills
Nopah Range
Artist's Drive
Blackfoot Valley
Neihart Ridge
McDonald Peak
Marias Pass
Cabinet Range
Naukluft Plateau
High Dune
Namib Dune
Helgas Dune
Kahani Dune
Marimba
Noctivaga Dune
Quela
Sebina
Old Soaker
Mt Desert Island
Ireson Hill
Ogunquit Beach
Nathan Bridges Dune
2004
2007
2009
2012
2014
2017
2020
METERS
0 500 1000
0 10 20
Projection: Equidistant Cylindrical, central longitude = 0, central latitude = 0, spherical Mars radius = 3396190 m
Data Sources: NASA/JPL-Caltech (traverse and place names) /Univ. of Az (HiRISE)/MSSS (CTX)/USGS (elevation data).
1m contour lines based on HiRISE DEM tied to MOLA elevation

MOUNT SHARP

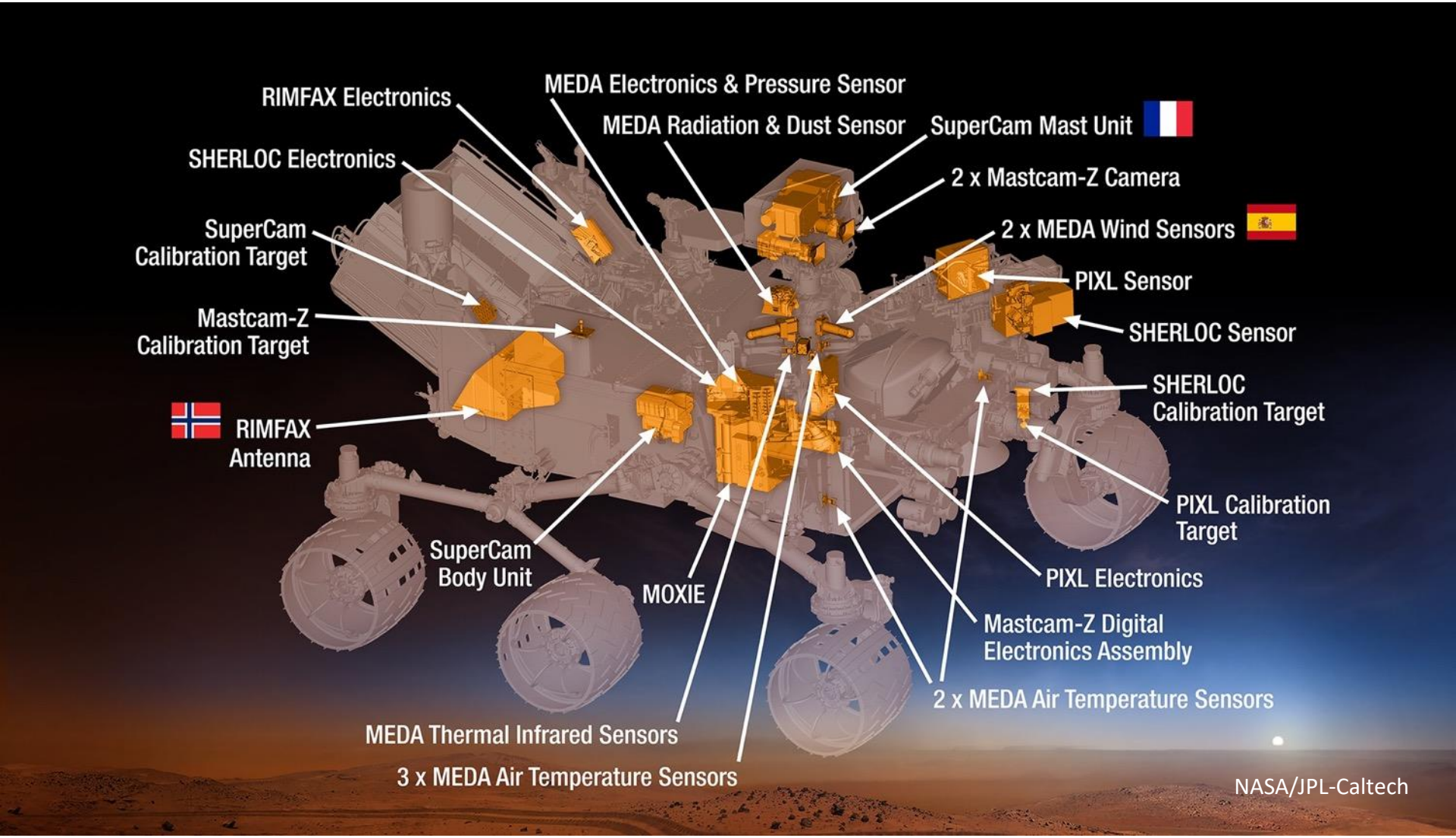

Sulfate Unit
Clay Unit
Hematite Unit
(Vera Rubin Ridge)
Murray Formation
NASA/JPL-Caltech/Goddard
NASA/JPL-Caltech/MSSS

EVOLVING SCIENCE STRATEGIES FOR MARS EXPLORATION

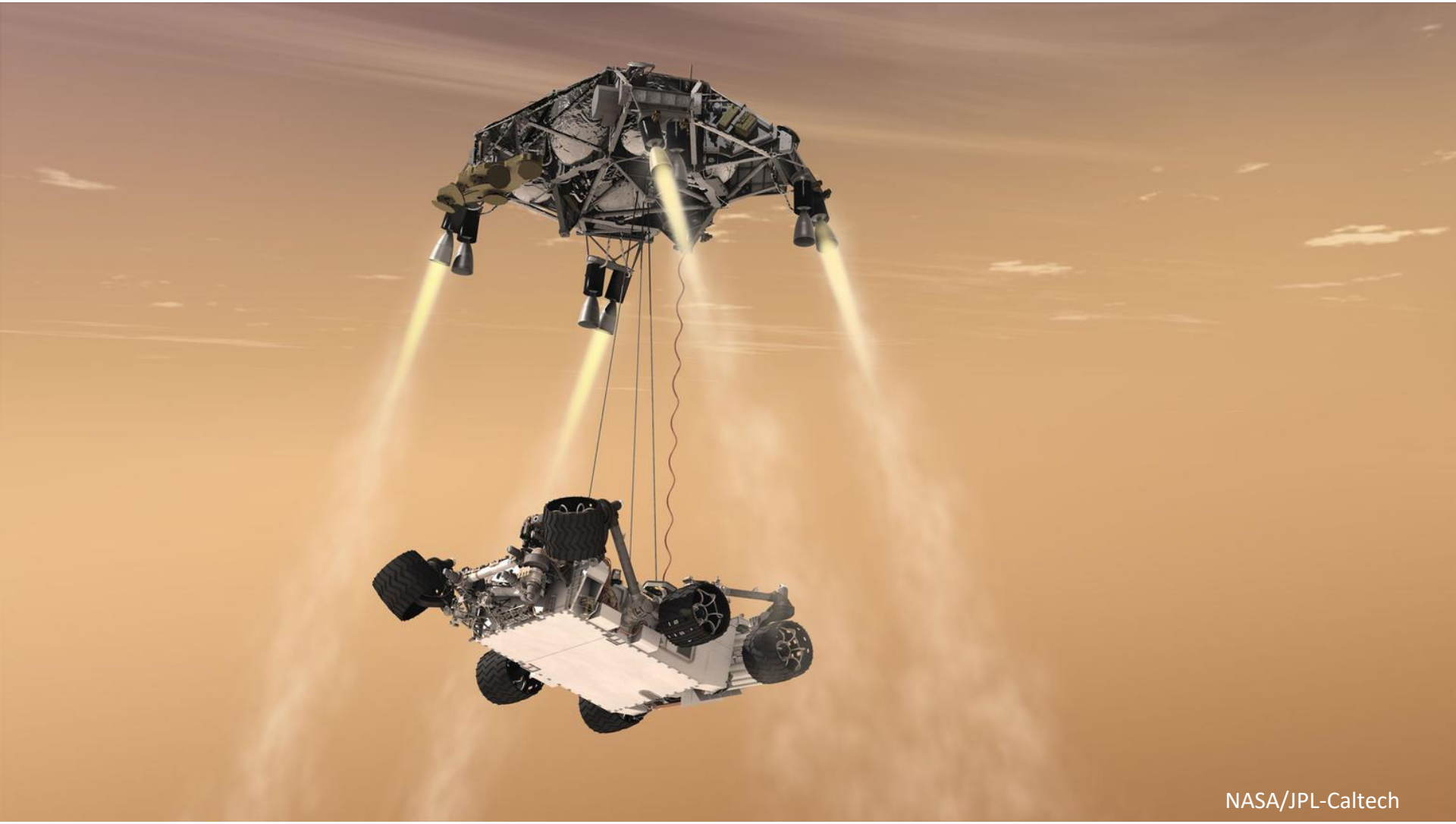


NASA/JPL-Caltech

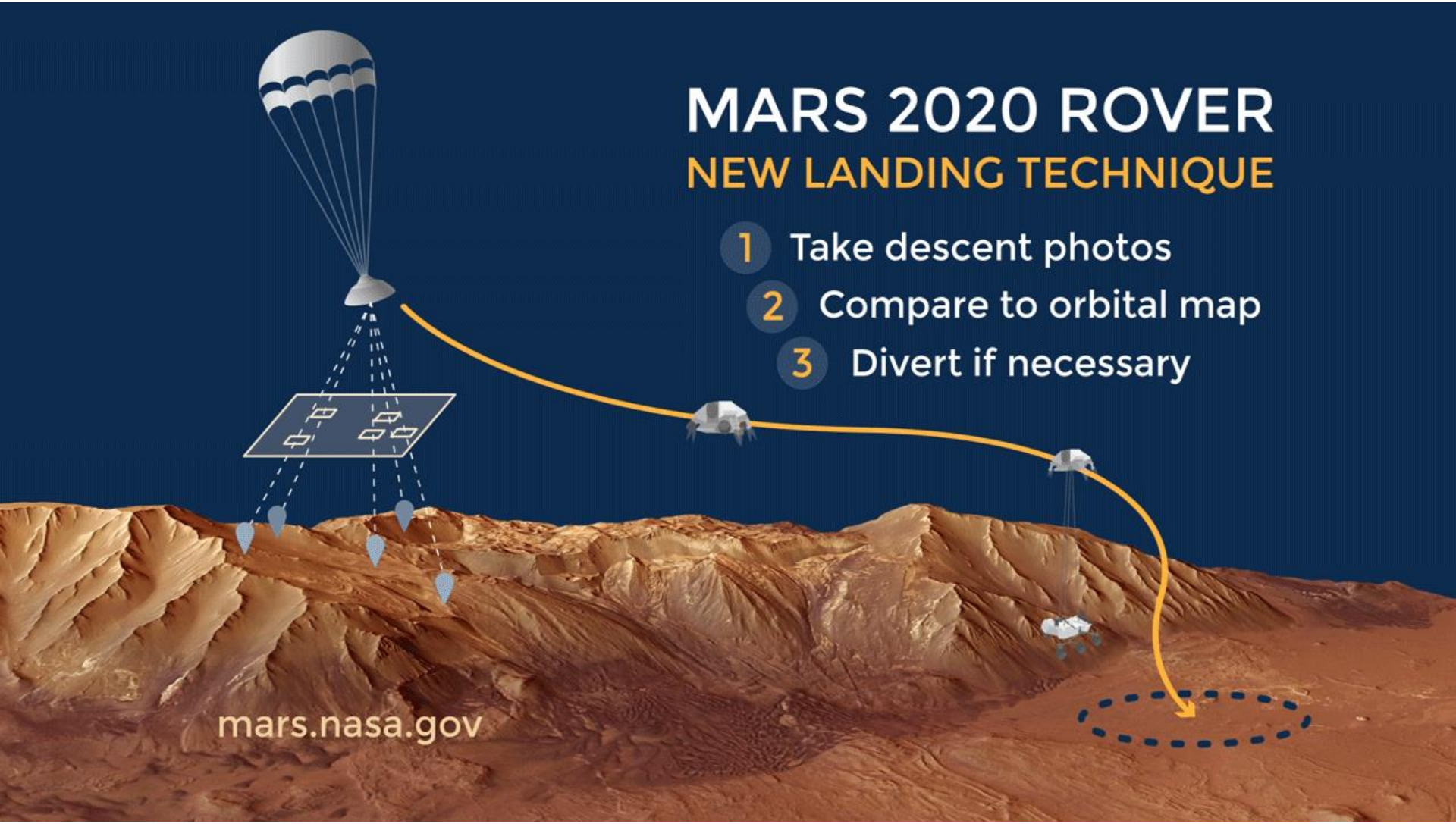
MARS 2020 ROVER



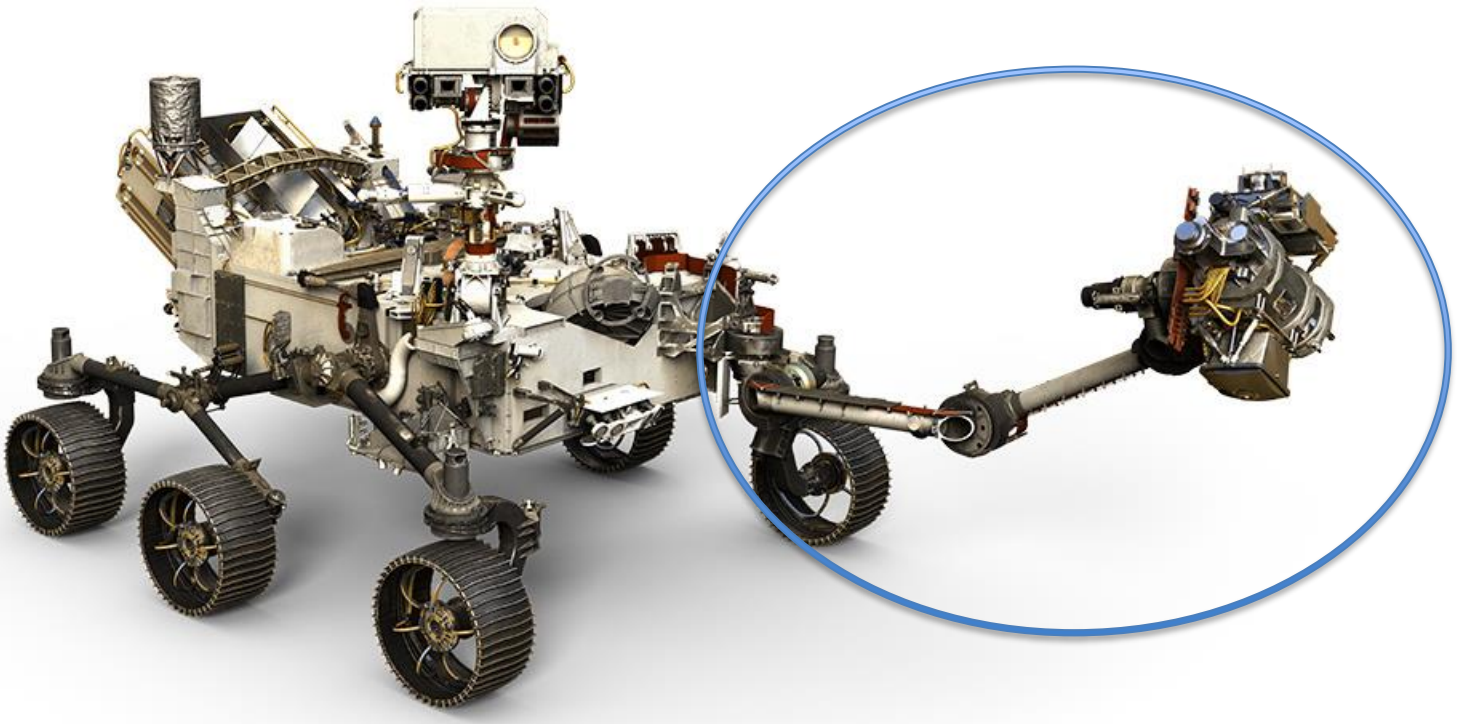
MARS 2020 ENTRY DESCENT AND LANDING



DIVERT MANEUVER

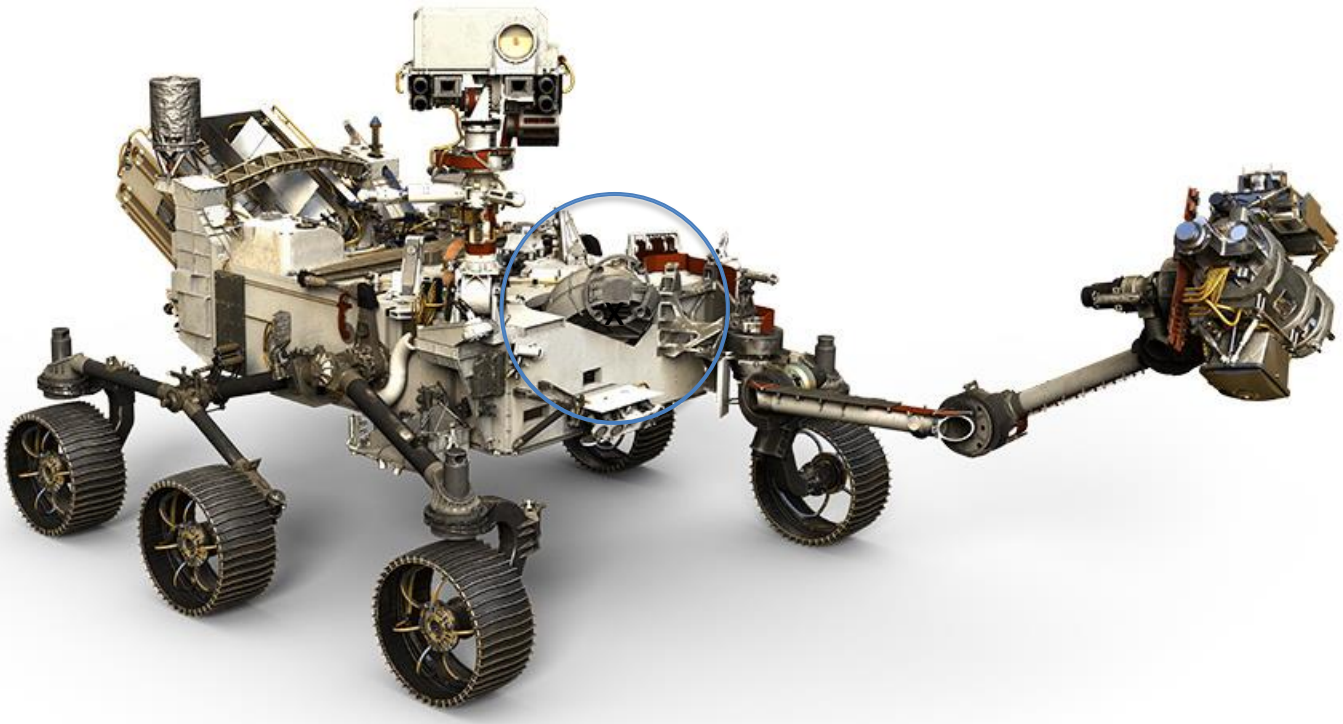


MARS 2020 ROBOTIC ARM AND TURRET



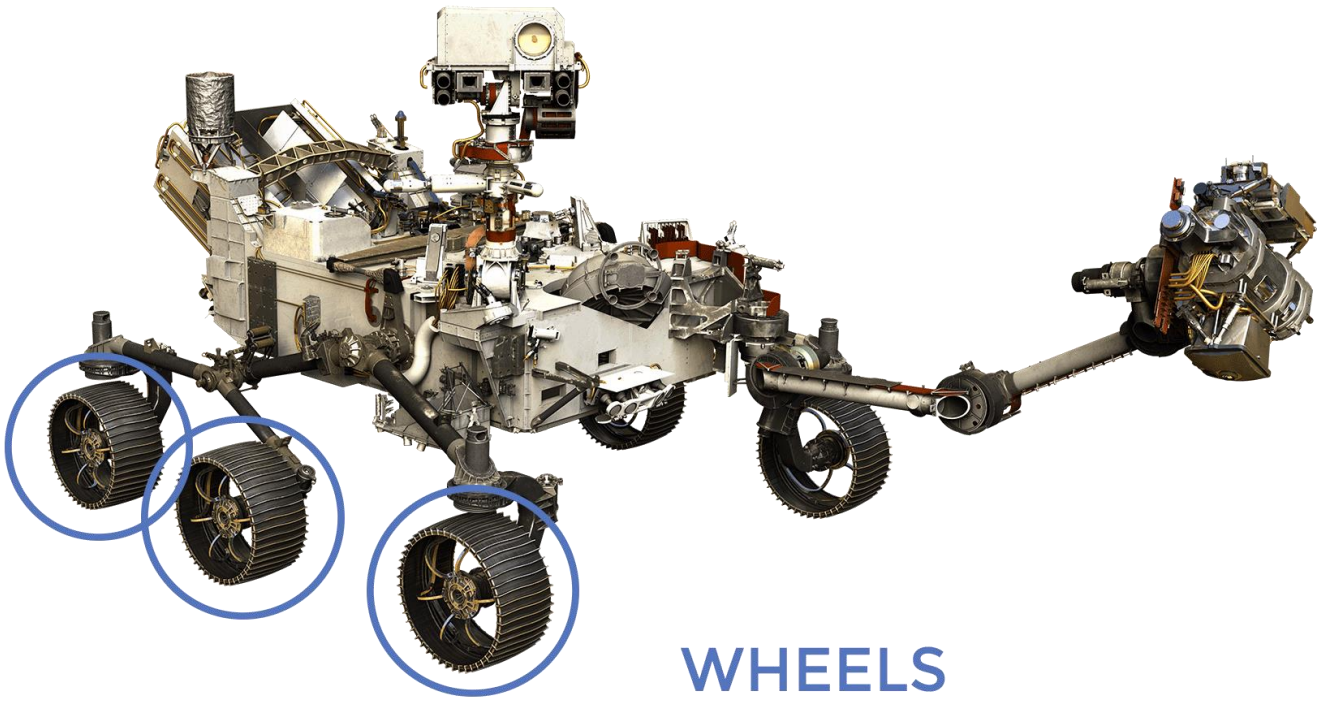
NASA/JPL-Caltech

MARS 2020 SAMPLE HANDLING



NASA/JPL-Caltech

MARS 2020 MOBILITY



NASA/JPL-Caltech

- NASA Jet Propulsion Laboratory / California Institute of Technology
  - https://jpl.nasa.gov/

NASA/JPL-C